

Rathke, G.E.

Diss. Mainz
1987



Digitized by the Internet Archive
in 2026

Towards ^{100}Sn :

Studies on Neutron - Deficient

Even Isotopes of Tin

Dissertation

zur Erlangung des Grades

"Doktor der Naturwissenschaften"

am Fachbereich Physik

der Johannes Gutenberg-Universität in Mainz

Gabriele-Elisabeth Rathke

geboren in München

Mainz 1986

1. Berichterstatter: Dr.habil. E. Roeckl

2. Berichterstatter: Prof. G. Huber

Tag der mündlichen Prüfung: 6. Februar 1987

Abstract:

Neutron-deficient $^{108,106,104}\text{Sn}$ isotopes were produced by heavy ion induced fusion reactions using high-intensity ^{58}Ni beams from the UNILAC of the GSI. Their decay properties were studied by techniques of gamma and conversion electron spectroscopy employing the mass separator on-line to the UNILAC. Earlier information on the $^{108}\text{Sn} \rightarrow ^{108}\text{In}$ and $^{106}\text{Sn} \rightarrow ^{106}\text{In}$ decays was complemented and improved in the course of this work. The new nucleus ^{104}Sn and its decay to excited states in ^{104}In was identified and studied for the first time. These investigations yield the following results: The mass of ^{104}Sn and of nuclei linked to it by alpha decay or proton radioactivity, ^{108}Te , ^{112}Xe and ^{109}I , ^{113}Cs , respectively were determined from the measured Q_{EC} value of ^{104}Sn and the known mass value of ^{104}In . These are nuclei very close or beyond the proton drip line. In addition, information on the quenching of the fast Gamow-Teller beta decay of the even neutron-deficient tin isotopes was obtained. This complements investigations on the $N = 50$ isotones ^{94}Ru and ^{96}Pd , and allows a systematic comparison of these transition strengths for nuclei near the doubly magic ^{100}Sn . The spreading of the $|\pi g_{9/2}^{-1} \nu g_{7/2}, 1^+ \rangle$ configuration over several states, due to residual interactions, and the centroid energies of these magnetic dipole states were determined for the corresponding odd-odd indium isotopes. The ground state masses of $^{110,108,106,104}\text{Sn}$ nuclei and the energies of the 1^+ states in the corresponding indium isotopes are found to be in good agreement with theoretical calculations. The observed Gamow-Teller strengths, however, are smaller, by factors up to four, than the best recent theoretical estimates. One reason for this discrepancy might be an underestimate of the role of pairing. In particular pairing between unlike nucleons could be important. It is suggested that these Gamow-Teller transitions are well suited to study the influence of higher order effects, including those due to the Δ -nucleon-hole excitation. Additional experimental information on the role of pairing, and of the 1^+ dipole state is needed to disentangle these phenomena. Suggestions are made to use the planned SIS - ESR facility of the GSI to study such questions in greater detail.

Table of Contents

1.0	Introduction	1
2.0	Goals and Range of This Study	5
3.0	Production, Separation and Spectroscopy of Nuclei near ^{100}Sn	7
3.1	Production Mechanisms for Exotic Nuclei: Nuclear Reaction Scenarios	7
3.2	Instrumentation	9
3.3	The GSI On-Line Mass Separator Facility	10
3.4	Entrance Channel Considerations for the Production of Neutron-Deficient Tin Isotopes	12
4.0	Experimental Procedures and Detector Arrays	16
5.0	Experimental Results: ^{110}Sn, ^{108}Sn, ^{106}Sn	23
5.1	The Isotope ^{110}Sn	23
5.2	The Isotope ^{108}Sn	23
5.3	The Isotope ^{106}Sn	23
6.0	Experimental Results: Decay Properties of the New Neutron-Deficient Nucleus ^{104}Sn	26
6.1	Identification and Half-life	26
6.2	Level Energies	29
6.3	Groundstate Q-Value	34
6.4	Spin Assignments	35
7.0	Discussion of Binding and Excitation Energies	37
7.1	Brief Description of the Models	38
7.2	Groundstate Q-Values for ^{110}Sn , ^{108}Sn , ^{106}Sn , ^{104}Sn	38
7.3	Center-of-Gravity Energies of 1^+ States	39
7.4	Mass Excess Values for ^{108}Te , ^{109}I , ^{112}Xe , and ^{113}Cs	40
7.5	Strength of the $Z = 50$ Proton Shell	42
8.0	The Gamow-Teller Beta Strength	43
8.1	Extreme Single Particle Model Considerations	43

8.2	Spreading of the Beta Strength to Several Final 1^+ States	45
8.3	Quenching of the Summed Beta Strength	47
9.0	Predicted Properties of ^{100}Sn and ^{100}In	51
10.0	Summary and Conclusions	53
11.0	References	57
12.0	Appendix	62
12.1	Danksagung	62
12.2	Curriculum Vitae	63

List of Illustrations

Figure 1. Chart of the nuclides	2
Figure 2. Section of the nuclidic chart	3
Figure 3. Principle of the ion source operation with bunched beam release	11
Figure 4. Example for the enhancement of indium (left) and cadmium (right)	12
Figure 5. Illustration of excitation energies in fusion reactions	13
Figure 6. Section of the singles spectra for mass 104	17
Figure 7. Experimental setup in 90 degrees geometry	19
Figure 8. Experimental setup in 180 degrees geometry	20
Figure 9. Experimental setup of the mini-orange type β -spectrometer	21
Figure 10. Electronics setup	22
Figure 11. Decay scheme of ^{106}Sn	24
Figure 12. Coincidence spectra of ^{106}Sn	25
Figure 13. Decay curve of ^{104}Sn	27
Figure 14. Coincidence spectrum of ^{104}Sn	27
Figure 15. Decay curve for the isomer in ^{104}In	29
Figure 16. Conversion electron spectra	30
Figure 17. Coincidence spectrum of ^{104}Sn	31
Figure 18. Coincidence spectrum of ^{104}Sn	31
Figure 19. Decay scheme of ^{104}Sn	33
Figure 20. Theoretical curve for the Q-value determination	34
Figure 21. Comparison of experimental and theoretical Q-values	39
Figure 22. Comparison of weighted 1^+ state sum energies	40
Figure 23. Illustration for the link to different masses	41
Figure 24. Estimate of the strength of the $Z = 50$ proton shell,	42
Figure 25. Theoretical shell model orbitals for ^{100}Sn	43
Figure 26. Compilation of the experimental information	46
Figure 27. Compilation of the effect of the different hindrance factors	50
Figure 28. Predicted decay scheme of ^{100}Sn	52

1.0 Introduction

Exploration of previously unknown regions of the nuclear chart has always been of major interest to nuclear science. The motivation is manifold: the investigation of nuclear matter under extreme conditions, like anomalous neutron-to-proton ratios or super-deformation, understanding nature's path in the production of the heavy elements found in the solar system, and probing the nucleon-nucleon interaction in nuclei far off the valley of stability. Reaching or passing the respective drip-lines allows one to investigate the direct emission of nucleons or nucleon clusters from the groundstate configurations.

Recently new heavy ion accelerator facilities have allowed to pursue these goals in various regions of the nuclear chart. Examples are the 'complete' map of light nuclei produced by projectile fragmentation at GANIL (see ref. [1]), the identification of the doubly magic $^{80}_{40}\text{Zr}$ nucleus (see ref. [2]) and of the superdeformed bands in rare earth nuclei (see ref. [3]) as studied via fusion-evaporation residue gamma ray techniques at Daresbury.

Fusion reactions as investigated at the UNILAC facilities of the GSI have been particularly useful to produce and identify the heaviest nuclei made up to now (see ref. [4]), and to map out the proton drip-line in the region $50 \leq Z \leq 82$ of the nuclear chart (see ref. [5]) as shown in Fig. 1. Such studies are of particular importance to improve our understanding of the fusion and re-separation of heavy colliding nuclei at energies close to the Coulomb barrier, where mean-field effects dominate, and to test the predictive power of various mass calculations in regions far off the valley of stable nuclei. These features then bear on the interplay between the macroscopic, i.e. liquid drop behaviour and the independent particle motion.

In this paper we report on recent efforts to study nuclei near the doubly magic ^{100}Sn nucleus. Such investigations have proceeded along two obvious routes (see Fig. 2).

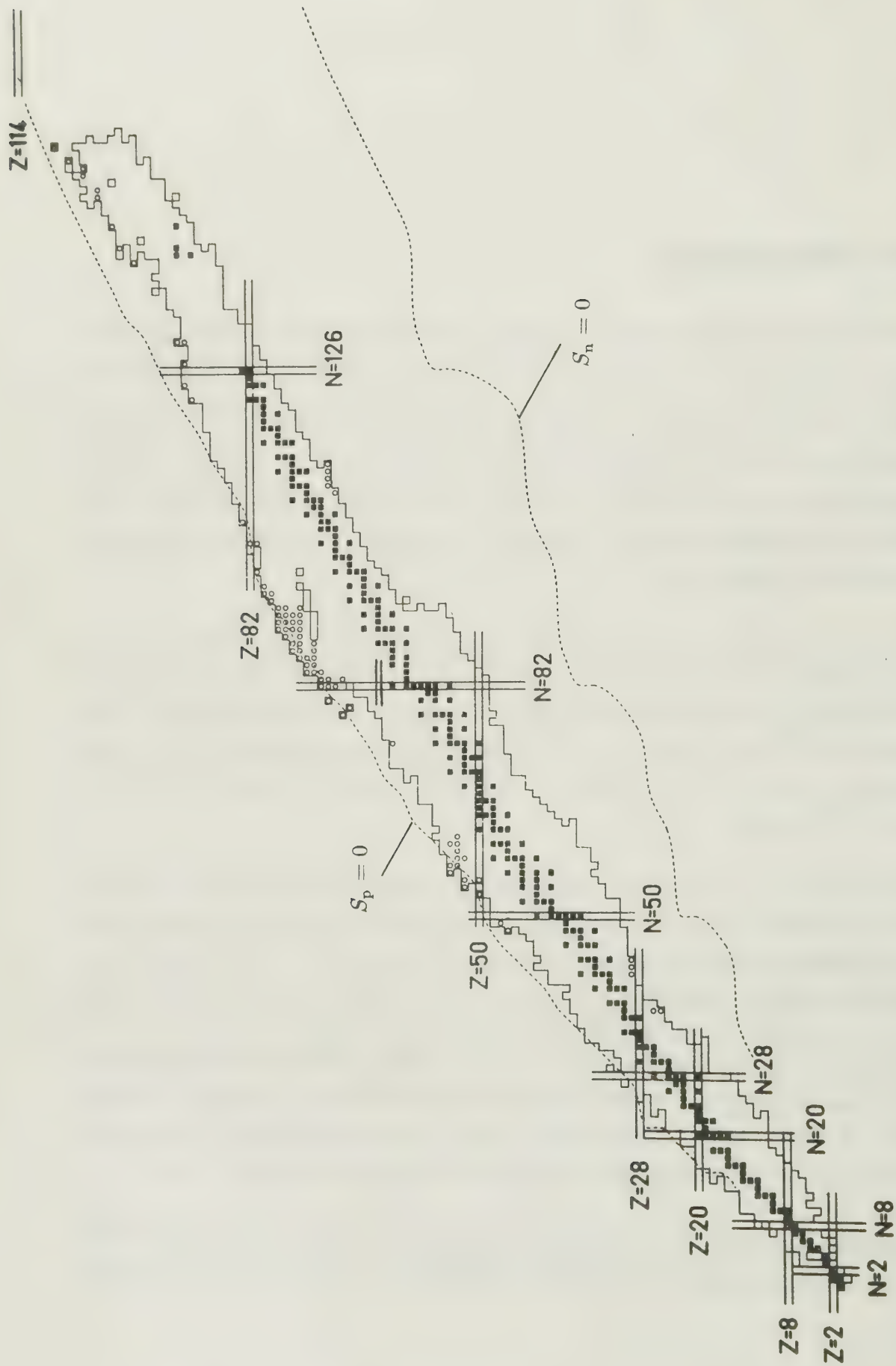


Figure 1. Chart of the nuclides. The solid lines indicate the region of known nuclei. Dotted lines show the proton and neutron drip lines, with separation energies S_p , $S_n = 0$. Open circles mark some of the new isotopes discovered at GSI. The figure is taken from ref. [4].

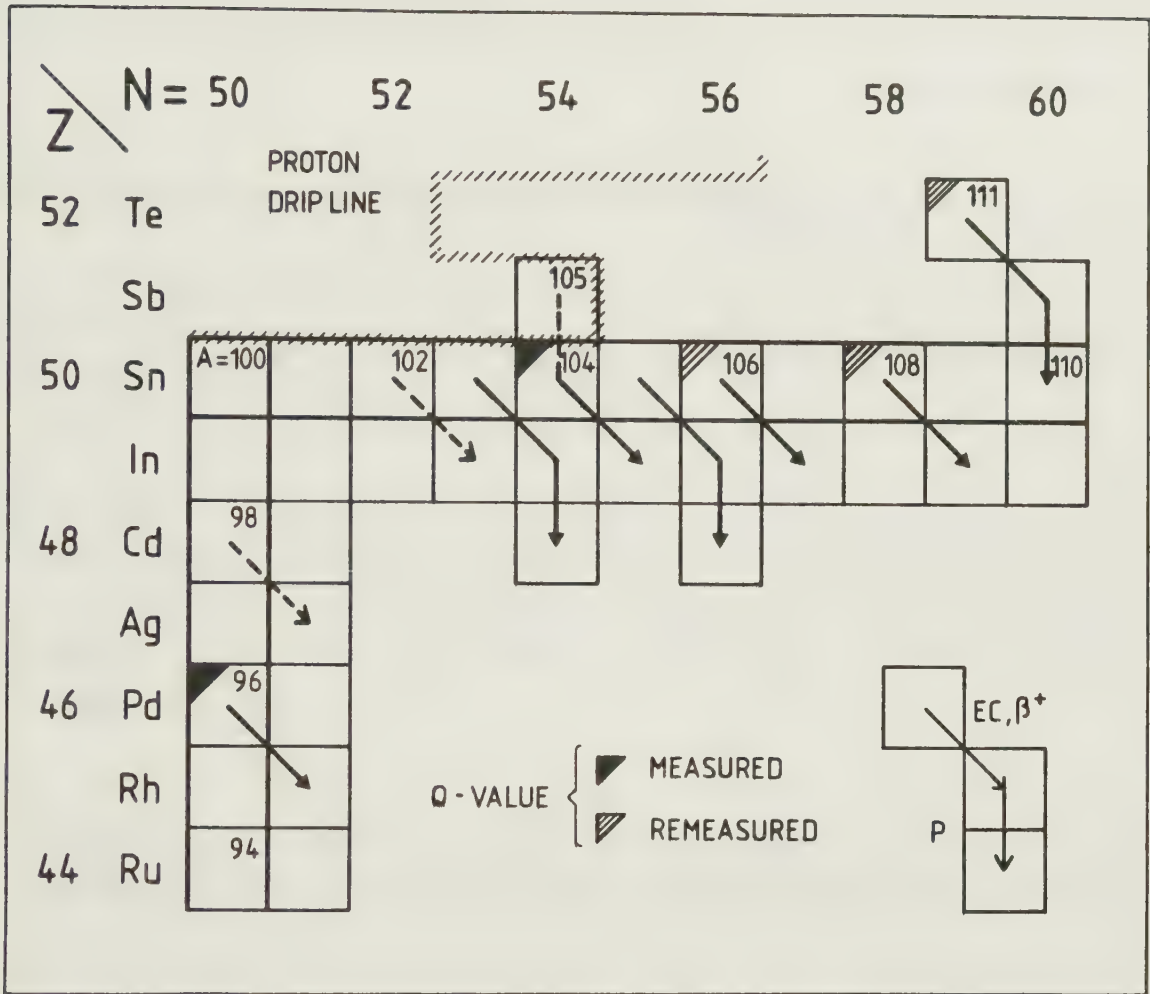


Figure 2. Section of the nuclidic chart to illustrate the two paths being followed to reach ^{100}Sn , along the $N = 50$ and $Z = 50$ lines; arrows indicate the decays studied (solid lines) and searched for (broken lines) in ref. [6] and the present work. The proton drip line from ref. [7] is shown with hatch-marks.

One is along the $N = 50$ isotones, by studying nuclei like $^{94}_{44}\text{Ru}$, $^{96}_{46}\text{Pd}$, and $^{98}_{48}\text{Cd}$. The other one proceeds via the $Z = 50$ isotopic chain, with $^{112}_{50}\text{Sn}_{62}$ being the lightest stable tin isotope and $^{106}_{50}\text{Sn}_{56}$ being the lightest even-even one for which at least some information was reported prior to our work on $^{104}_{50}\text{Sn}_{54}$ (see ref. [8]).

Here we concentrate on the latter concept. The neutron-deficient tin isotopes are produced by heavy ion fusion reactions and separated by the mass-separator on-line to the UNILAC (see ref. [9]). Subsequently their decay properties are studied by the techniques of nuclear spectroscopy. We have improved and complemented the ex-

isting information on the even $^{108,106}\text{Sn}$ nuclei, and have studied the previously unknown ^{104}Sn nucleus for the first time (see ref. [10]). The results not only allow to discuss nuclear binding and decay properties of these nuclei, but also to extrapolate on the production of the doubly magic ^{100}Sn , and on its properties in terms of existing calculations.

2.0 Goals and Range of This Study

As mentioned above we try to approach the ^{100}Sn nucleus via the $Z = 50$ isotopic chain. In addition to the more general motivation quoted above we have some very specific questions to be studied for these nuclei.

1. The 'stability' of the $Z = 50$ proton shell closure against variations of the neutron number within a whole major shell, $50 \leq N \leq 82$, i.e. the influence of the neutron-proton interaction on the magic proton core. Information on excited states in the $_{49}\text{In}$ proton-hole neutron-particle multiplets might be of particular use in this respect.
2. The build-up of collectivity, i.e. the suprafluid neutron-paired groundstate configuration, when more neutrons are added in shell model orbitals near the Fermi-surface.
3. The interplay of more deformed neutron configurations with the spherical $Z = 50$ proton shell.
4. The absolute magnitude and spreading of the Gamow-Teller (GT) strength in nuclear beta decay, as observed in the $(\pi g_{9/2}^n)_{0+} \rightarrow (\pi g_{9/2}^{n-1} \nu g_{7/2})_{1+}$ transitions in such nuclei.

The absolute magnitude of the GT transition strength is of general interest, because it measures a possible modification of the free nucleon properties in nuclei. The nuclear beta decay measurements are related to studies of (p,n) and (n,p) reactions (see refs. [11,12]) which bear on the 'inverse beta decay processes', and to electron scattering experiments (see ref. [13]) which investigate the M1 spin-flip excitations in nuclei. In all these experiments one finds only part of the transition strength as predicted by single particle model calculations. This quenching of the GT strength

has been discussed in great detail recently, in particular the influence of pairing, core polarization and higher order excitations. An important one might be the excitation of Δ resonances (see ref. [14]). As will be shown nuclei near ^{100}Sn are well suited to study the influence of these higher order effects.

The fractionating of the GT strength, i.e. the appearance of several final 1^+ states may be a rather unique possibility to explore the influence of deformation on the neutron-proton interaction.

In order to study these questions in some detail we need a systematic experimental information on groundstate mass excess (ME) values or ME differences such as the groundstate-to-groundstate decay energy for electron-capture (Q_{EC}), on the excitation energies and splitting of the 1^+ states in indium nuclei, and on GT transition probabilities. This was the goal of the present investigation. Complementary experiments along the $N = 50$ isotonic route are being pursued at the ISOLDE facility at CERN (see ref. [15]).

3.0 Production, Separation and Spectroscopy of Nuclei near ^{100}Sn

In this section we first briefly summarize the techniques which have been used to produce and investigate ‘exotic’ nuclei far off stability. We **exclude** the production and identification of the heaviest ones, up to $Z \cong 110$, via fusion reactions (see ref. [4]), and concentrate on nuclei between the valley of stability and the nucleon drip lines, with masses below $A \cong 200$. We then apply these arguments to nuclei near ^{100}Sn and discuss the experimental concept which was used in the present investigation.

3.1 *Production Mechanisms for Exotic Nuclei: Nuclear Reaction Scenarios*

According to present experience nuclei far off stability are produced by nuclear disintegrations and/or reactions of the following type:

1. **Fission** of nuclei near ^{238}U ; the products are neutron-rich, yields are high for nuclei with $100 \leq A \leq 140$. Most remarkable in the context of this work is the production and investigation of the nucleus $^{132}_{50}\text{Sn}_{82}$ (see ref. [16]).
2. **Fusion and Incomplete Fusion:** The products are proton-rich, up to the drip line. According to the Groningen analysis (see ref. [17]) and general experience incomplete fusion processes are limited to projectiles with $A \leq 40$, and begin to dominate above 10 MeV/u incident energy, due to angular momentum arguments.

It is not clear, however, which process is more advantageous to produce the very neutron-deficient nuclei, fusion or incomplete fusion. A quantitative comparison of reactions like $^{92}\text{Mo} (^{16}\text{O}, 4n) ^{104}\text{Sn}$ or $^{92}\text{Mo} (^{20}\text{Ne}, \alpha 4n) ^{104}\text{Sn}$ has never been made, to our knowledge. For more details about fusion reactions see also chapter 3.4.

3. **Spallation**, induced by high-energy protons: This process, as well as fission, have been used by the CERN-ISOLDE group successfully over many years. For neutron-deficient tin nuclei the present ISOLDE yields are insufficient for our purposes (see ref. [18]), whereas ^{98}Cd may be produced in some quantities, employing a molten tin target. Neutron-deficient indium isotopes are more advantageously produced by fusion using high current ^{16}O or ^{40}Ca beams of the UNILAC (see ref. [5]).
4. **Projectile Fragmentation**: Since the first studies of this type at LBL (see ref. [19]) this process is understood as a non-adiabatic splitting of a fast projectile, especially suited to produce neutron-rich light nuclei. Recent work at GANIL (see ref. [1]) has demonstrated, at least for lighter ($A \leq 40$) systems that also the proton drip line can be reached. In order to produce exotic heavier nuclei with appreciable yields one needs a high- current high-energy heavy ion accelerator, such as the planned SIS-ESR facility at GSI (see ref. [20]).
5. **Multinucleon Transfer**: Transfer reactions at incident energies near the Coulomb barrier can result in either neutron- or proton-rich flow depending on the characteristics of the colliding nuclei (see ref. [21]). However, the yield is generally split between very many channels, and conditions under which the final 'exotic' nuclei survive against fission or nucleon evaporation have to be carefully prepared. 'Cold' transfer processes have been observed in several systems, but are only partially understood. Practical experience shows that surface-dominated processes still are of great importance for the production of cold nuclei far off the injection point of the nuclear reaction.

Transfer reactions studies at the highest energies available at the UNILAC, for instance for the $\text{Mo} + \text{Mo}$ system have been shown to produce practically all nuclei up to the combined system mass (see ref. [22]). However, the yield per isotope is low, and most of the fragments are highly excited. One therefore expects that exotic products will survive rather seldom and highly selective separation mechanisms are needed.

Despite of these shortcomings transfer reactions may be of great use, in particular in the course towards very neutron-rich nuclei. With the availability of high-intensity heavy-ion beams with energies ranging up to 20 MeV/u at the UNILAC, the Göttingen-GSI-Mainz-Warsaw collaboration has successfully produced neutron-rich isotopes in the areas below the light and above the heavy fragments of asymmetric fission ($Z \leq 29$ and $Z \geq 66$, respectively). A review of the obtained spectroscopic results and references can be found in ref. [23], while an application of the techniques to an astrophysical problem concerning the abundance of ^{180}Ta is presented in ref. [24].

3.2 Instrumentation

Since exotic nuclei are always produced with a low yield, with a high background in general and of neighbouring nuclei in particular, highly selective separation and identification techniques are needed. As demonstrated recently for the ^{80}Zr nucleus (see ref. [2]), coincidence measurements with light evaporated particles, in particular neutrons, are not sufficient to separate channels with μb cross sections out of the $\cong 1$ barn reaction cross section, due to the low solid angle and efficiency of the systems used to detect the light particles. However, coincidences with the evaporation residue proper, with their high detection efficiency have it made possible to identify such a weak channel. These experiments are only possible in connection with a recoil separator of high mass resolution.

We thus restrict the discussion here on the comparison of mass separators on-line and recoil spectrometers. Among the latter we concentrate on velocity filter systems as used up to now for incident energies near the barrier. For much higher energies 0° magnetic spectrometers such as LISE (see ref. [25]) are more appropriate, mainly because the electric rigidity of the velocity filter systems becomes insufficient, and projectile fragmentation begins to dominate, with all the fragments having close to beam velocities.

Mass separators on-line can use quite thick targets and all types of nuclear reactions. They are not restricted to heavy ion beams, have excellent mass resolution and suppression of adjacent masses. However, they are rather 'slow' devices; halflives

must be of the order of 10 ms. Until recently they could not differentiate against the high isobaric background.

Recoil separators are useful to study evaporation residues from heavy ion induced fusion; thus they are restricted to incident energies of heavy ions near the Coulomb barrier. Collection efficiencies are high, and only limited by the solid angle of the instrument and charge state distribution of the evaporation residues emerging from the target. They are rather fast devices, with typical flight times around 10 μ s. Due to the high recoil velocity the evaporation residues can be uniquely identified with respect to their nuclear charge by a ΔE -E technique.

Recoil separators with full mass separation are just coming in use. Therefore isotope separators on-line have dominated the field up to now. The present investigation was performed with the system installed at the UNILAC.

In the following we briefly describe the main features of the system used at GSI, in particular the recent development of an ion source with **bunched** beam release (see ref. [26]) which has made it possible to remedy one of the previous limitations of such systems, namely the high isobaric background.

3.3 *The GSI On-Line Mass Separator Facility*

The GSI on-line mass separator uses reionization of the radioactive nuclei produced in an ion source, and reacceleration of singly-charged ions to $\cong 50$ keV. The resulting mass separated beams are used in the present work for preparing point-like sources for beta- and gamma-decay spectroscopy.

Two types of ion sources are in use: the **forced-electron-beam-induced-arc-discharge** (FEBIAD) source and a high temperature cavity thermoionizer. The present work is performed with the FEBIAD source (see ref. [27]).

Recently the possibility of bunching the released ion beam has been explored and added to these sources. The operation principle, as indicated in Fig. 3, consists of accumulating atoms in a cold trap inside the ion source and in then inducing a fast emission by heating this trap.

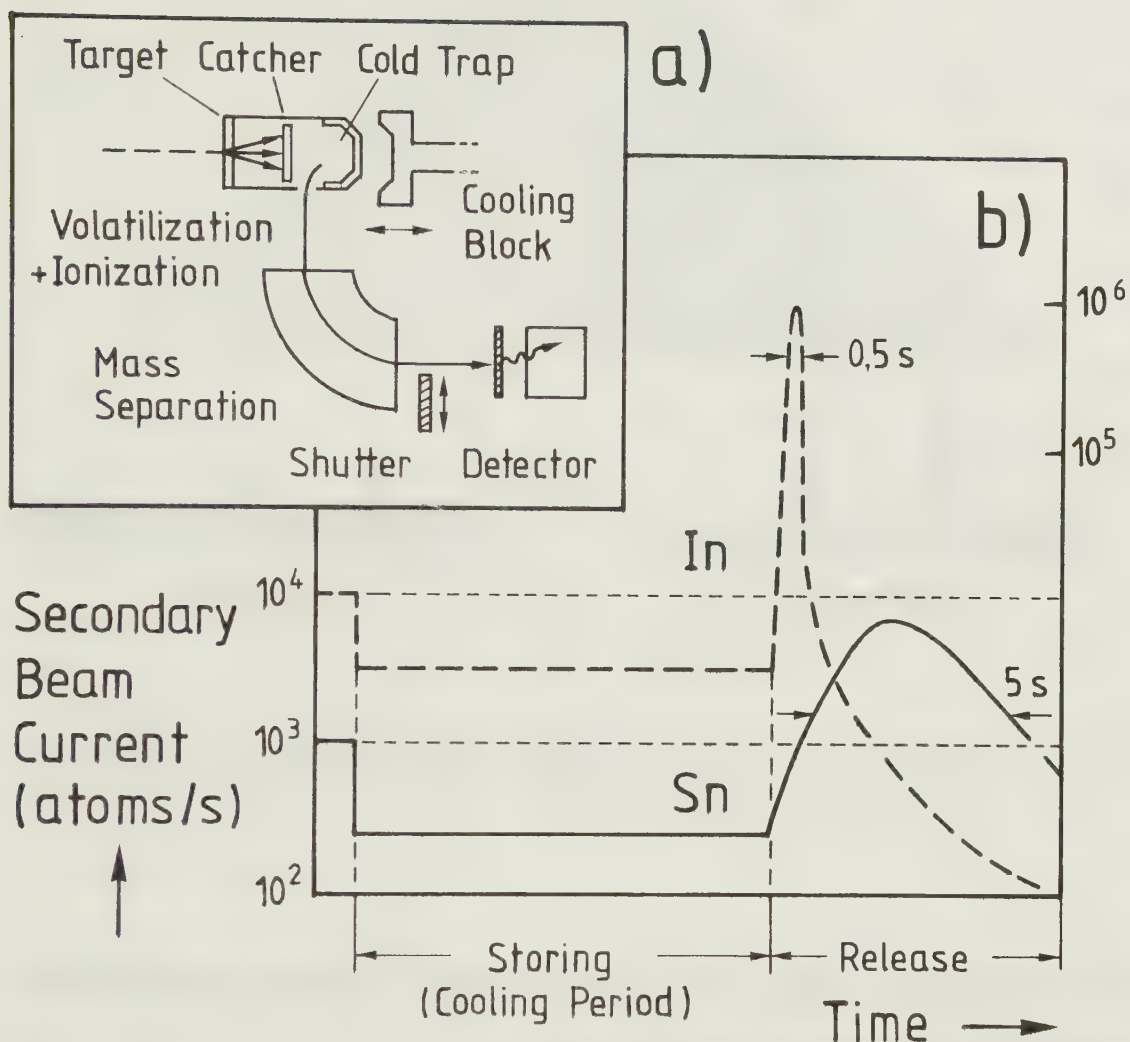


Figure 3. Principle of the ion source operation with bunched beam release
a) shows a sketch of the ion source with the pocket for cooling
b) the different release behaviour of indium and tin in a very systematic way, the two curves are achieved with two different ion sources.
The figure is taken from ref. [28].

The shape of the release time profile is mainly determined by the adsorption enthalpy with respect to the surface of the trap and thus allows chemical separations by setting time windows in a cooling/heating cycle. Examples of indium and cadmium chemistry are shown in Fig. 4, and it is interesting to note that the enrichment of different elements is done simultaneously in one and the same experiment. This novel

method of on-line chemistry in the ion source yields not only cleaner decay spectra, but allows element assignment from measured ratios of DC and bunched beam intensities.

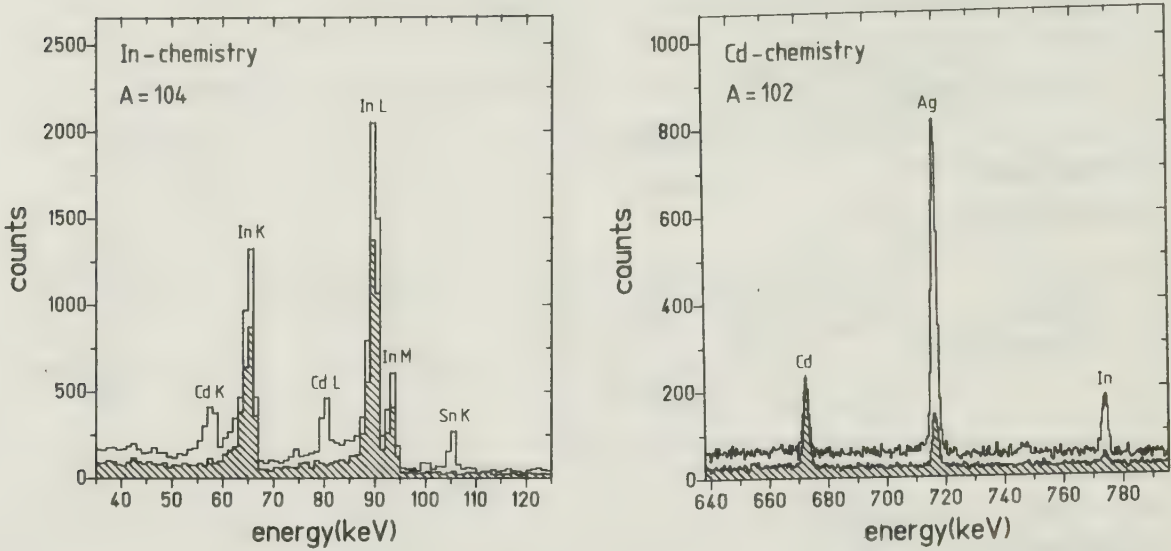


Figure 4. Example for the enhancement of indium (left) and cadmium (right) suppressing the isobaric background by setting a proper time window, see text and Fig. 3.

3.4 Entrance Channel Considerations for the Production of Neutron-Deficient Tin Isotopes

As discussed above only heavy ion fusion reactions appear to be suited to produce these tin isotopes in useful quantities. However, as can be deduced from Fig. 5, 'cold' fusion cannot be achieved in these processes, with excitation energies of the compound nuclei always being at least 30 MeV for very asymmetric systems, or > 45 MeV for the more symmetric ones, at incident energies close to the barrier.

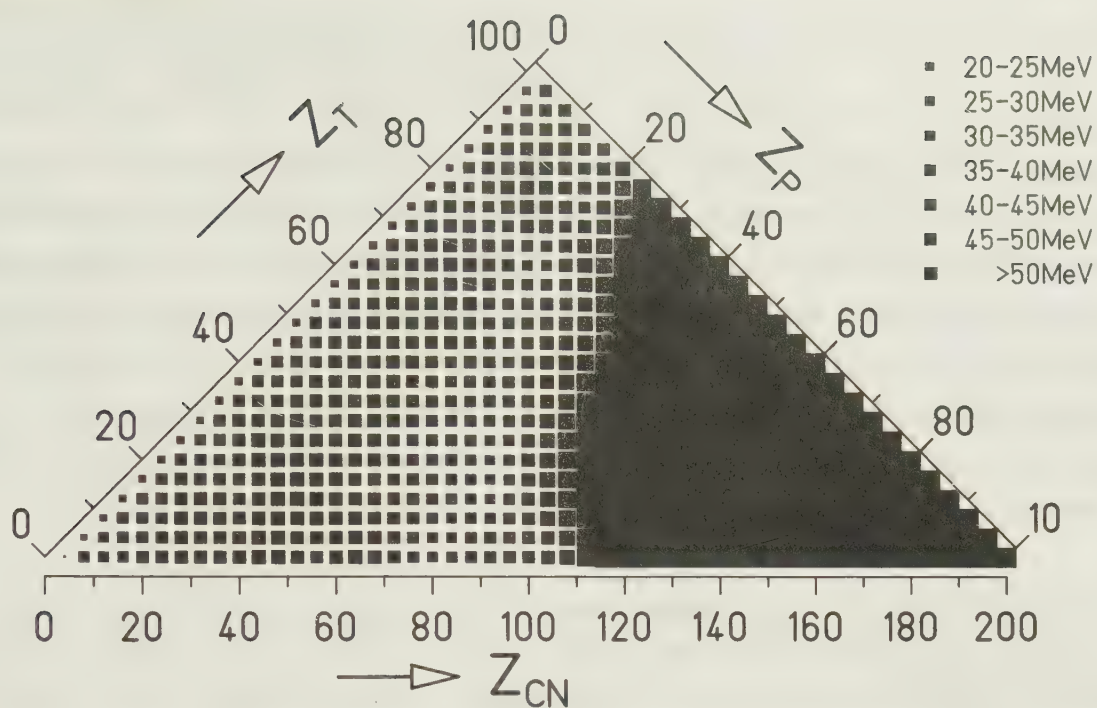
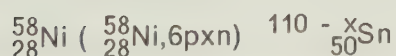
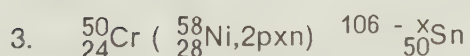
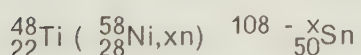
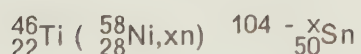
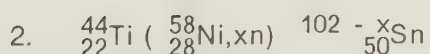


Figure 5. Illustration of excitation energies in fusion reactions (taken from ref. [4])

We consider the following production channels:



The first two reactions (1.) have been successfully used to produce tin isotopes down to $A = 104$, i.e. the $4n$ channel was observed (see e.g. refs. [29,30]). An advantage of these reactions is the high beam current possible with the ^{16}O , ^{20}Ne projectiles. On the other hand, the high neutron multiplicity needed to produce the very neutron-deficient tin isotopes is disadvantageous for the following reasons: Since the excitation energy of the compound nucleus at the barrier is rather low we have to use bombarding energies way above the barrier and can thus exploit only the low partial wave fraction of the compound nucleus formation cross section. Since the ratio of reduced widths for neutron and proton evaporation, (Γ_n / Γ_p) , is smaller than one and enters n times for n evaporated neutrons, we expect the isobaric indium and cadmium background to grow rapidly with the number of evaporated neutrons.

Reactions of type 2 look attractive especially if one had a radioactive ^{44}Ti target available. The problem is the high excitation energy of the compound nucleus which favours the evaporation of 4 to 6 nucleons already at barrier incident energies. Again the proton evaporation is expected to dominate strongly, and we expect a high isobaric background.

Therefore we consider the $^{58}\text{Ni} + ^{50}\text{Cr}$, ^{58}Ni reactions at energies slightly above the barrier to be an optimum choice to evaporate 4 to 6 nucleons, and among those up to 2 neutrons, and thus to produce $^{104,106,108}\text{Sn}$ with a tolerable isobaric background.

Such qualitative arguing was tested by calculations with the statistical evaporation code HIVAP (see ref. [31]). It uses standard evaporation theory (see refs. [32,33]) taking into account competition between neutron, proton, alpha, and gamma decay, as well as fission and a revised level density formula depending on angular momentum. HIVAP is generally found to reproduce measured excitation functions reasonably well.

Since absolute yields are not measured in our experiment we can only compare the general trends in experimentally determined yields with the HIVAP calculations; and these are in reasonable agreement with each other. We thus verify the experimental finding that the absolute yield of ^{104}Sn nuclei using ^{16}O or ^{58}Ni beams, respectively, is about equal, due to the higher current of the ^{16}O beam intensity and thicker target, but isobaric contaminations of ^{104}In , ^{104}Cd , and ^{104}Ag are more than an order of magnitude stronger in the ^{16}O induced reaction. The same high isobaric

background was calculated for reactions using the $^{46,48}\text{Ti}$ targets, again in agreement with experimental investigations.

Table 1 summarizes results for a 4.8 MeV/u ^{58}Ni beam of 50 particle nA intensity incident on a 3.5 mg/cm² ^{50}Cr target and mass A = 104. Column 1 gives the calculated numbers of nuclei in the target, column 2 the activity in the counting position as deduced from the gamma ray spectroscopic information. If we assume that the calculated values are correct, we can derive a 'mass separator efficiency' of 2.6 %, 20 %, and 28 % for tin, indium, and cadmium, respectively. Column 3 refers to the bunched beam release mode of the FEBIAD-B2 ion source (see also chapters 3.3 and 4.0).

nucleus	HIVAP [s ⁻¹]	exp. values in DC mode [s ⁻¹]	reduction factors in bunched mode optimized for Sn In	
^{104}Sn	7×10^4	1.8×10^3	3	> 600
^{104}In	5×10^5	1.0×10^5	135	1.3
^{104}Cd	8×10^5	2.2×10^5	45	60
^{104}Ag	-	6×10^4	30	

Table 1: Column 1: calculated number of nuclei produced in the target (using the code HIVAP [31]
Column 2: experimental yields after mass separation
Column 3: reduction factor in bunched mode optimized for tin or indium.
All numbers are given for 50 partnA of 4.8 Mev/u. ^{58}Ni on a 3.5 mg/cm² target of ^{50}Cr .

4.0 Experimental Procedures and Detector Arrays

The experiments were performed at the GSI mass separator on-line to the UNILAC. Beams of $\cong 5$ MeV/u $^{58}\text{Ni}^{13+,14+}$ ions incident on highly enriched ^{50}Cr and ^{58}Ni targets of $\cong 4$ mg/cm² areal density were used to produce and investigate the decay of the $^{104,106,108}\text{Sn}$ nuclei. Details are summarized in Table 2.

evaporation residue	beam	target
^{108}Sn	$^{58}\text{Ni}^{14+}$ 5.0 MeV/u	^{58}Ni (97.5 %) 4.14 mg/cm ²
^{106}Sn	$^{58}\text{Ni}^{14+}$ 5.0 MeV/u	^{58}Ni (97.5 %) 3.70 mg/cm ²
^{104}Sn	$^{58}\text{Ni}^{13+, 14+}$ 4.8 MeV/u	^{50}Cr (96.8 %) 3.40 mg/cm ²

Table 2: Compilation of beams and targets used for the production of the light even tin isotopes.

The bombarding energy was chosen to optimize the yield of the $^{106,108}\text{Sn}$ isotopes, respectively. In these cases radioactivity from the neighbouring isobars did not cause any serious complication. Such a choice was not possible for $A = 104$. The bombarding energy of 4.8 MeV/u was found to optimize the ^{104}Sn yield. However, the measured yield for ^{104}In ($T_{1/2} = 115$ s) is nearly two orders of magnitude stronger than for ^{104}Sn ($T_{1/2} = 21$ s).

Therefore the chemical selection by the bunched release mode of the ion source was not only useful for the assignment of gamma lines to certain nuclei, but absolutely necessary for the investigation of the ^{104}Sn decay. In gamma spectroscopy of ^{104}Sn enhancement of tin by factors of approximately 10, 15, and 45 over silver,

cadmium, and indium, respectively, were measured, sacrificing (only) 70 % of the total tin intensity (see Table 1). An example is shown in Fig. 6.

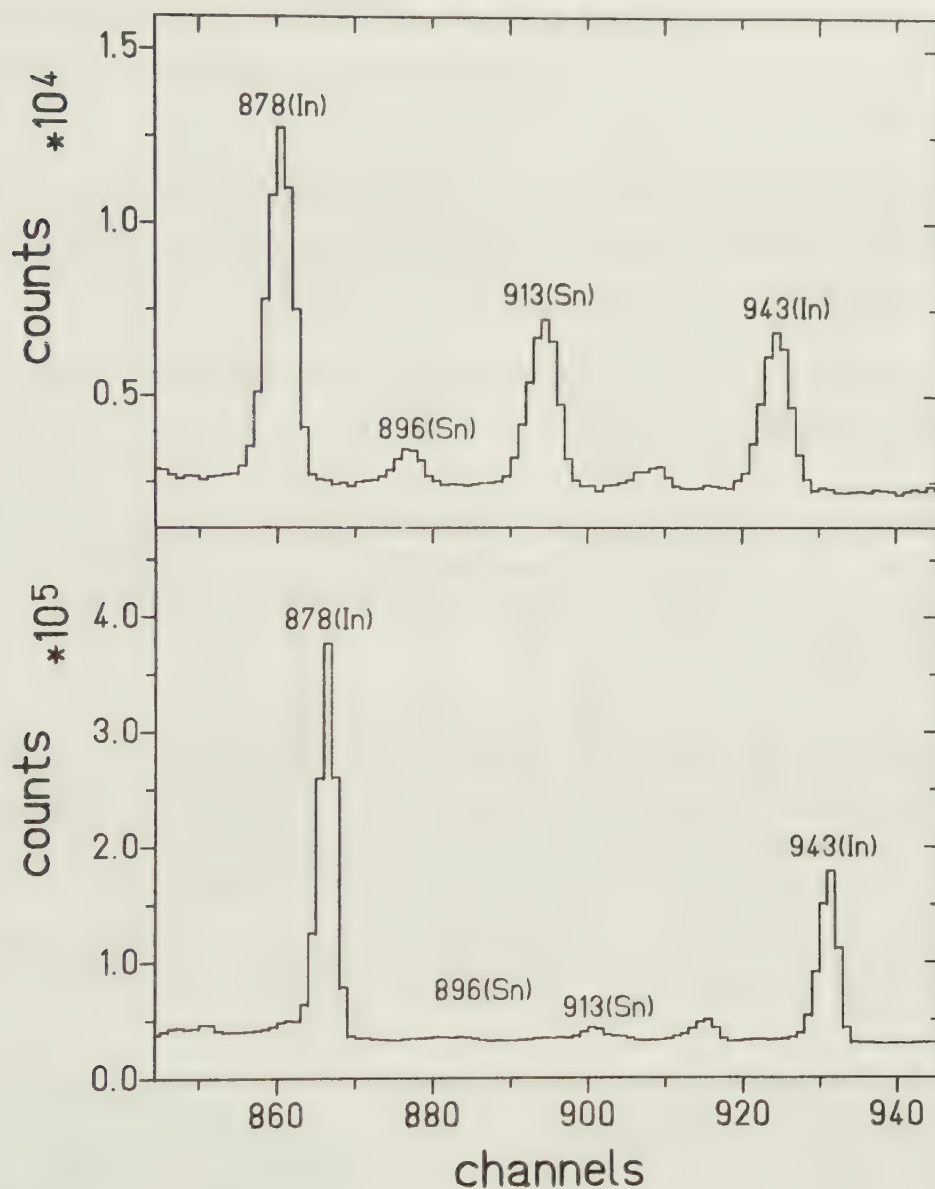


Figure 6. Section of the singles spectra for mass 104 showing the effect of the bunched beam release mode of the ion source. The upper part shows a spectrum, accumulated for 19 h with a 30 % Ge detector with **bunched beam release** optimized for tin, whereas the lower shows the same section of the spectrum, measured in **DC mode** for 21 h with a 34 % Ge detector.

The target thickness was chosen in such a way that the high-yield part of the excitation function was sufficiently covered, and that the evaporation residues had

enough energy to penetrate the $800 \mu\text{g}/\text{cm}^2$ Ta metal entrance window of the ion source.

As such metallic self-supporting chromium and nickel targets of $\cong 4 \text{ mg}/\text{cm}^2$ areal density cannot stand more than 30 particle nA of nickel beam they were modified in the case of chromium in two ways to improve mechanical stability and dissipation of thermal heat:

1. The target was covered with a copper layer of the same thickness on the upstream side. The bombarding energy was raised in this case to compensate for the energy loss in the copper layer.
2. A copper sieve of $\cong 70 \%$ transmission was mounted in close contact on both sides of the target.

The evaporation residues are extracted as singly charged ions from the source, accelerated to $\cong 50 \text{ keV}$, separated according to their mass and deposited on a tape system which can be moved at chosen intervals to transport the activity to the counting position.

Typical collection times are seconds to hundreds of seconds, and the motion of the activity into the counting position takes around 0.2 s. Counting of the singles spectra is synchronized with the tape transport, and time-dependent singles spectra are accumulated for decay constant determinations (multispectrum analysis). Gamma-gamma and gamma-electron coincidences are also counted but not cut into bins with respect to the tape motion.

The overall efficiency of the whole system is known from various test runs and previous experiments to be between 2 and 20 %, i.e. from typically 10^5 nuclei produced per second in the target, $\cong 10^4$ decay in front of the germanium detectors. Actual numbers are given in Table 1.

Typical singles rates in these (photopeak efficiency for 300 keV gamma-lines $\cong 10 \%$) are thus 1 to 5 times $10^3/\text{s}$. For ^{104}Sn , with only a few percent of the total yield of 7×10^4 atoms/s this leaves a very low activity, indeed.

Three different setups were used for the decay studies:

1. Two large ($\cong 30\%$) Ge(Li) detectors in a 90° geometry and a third one on the opposite side, see Fig. 7.

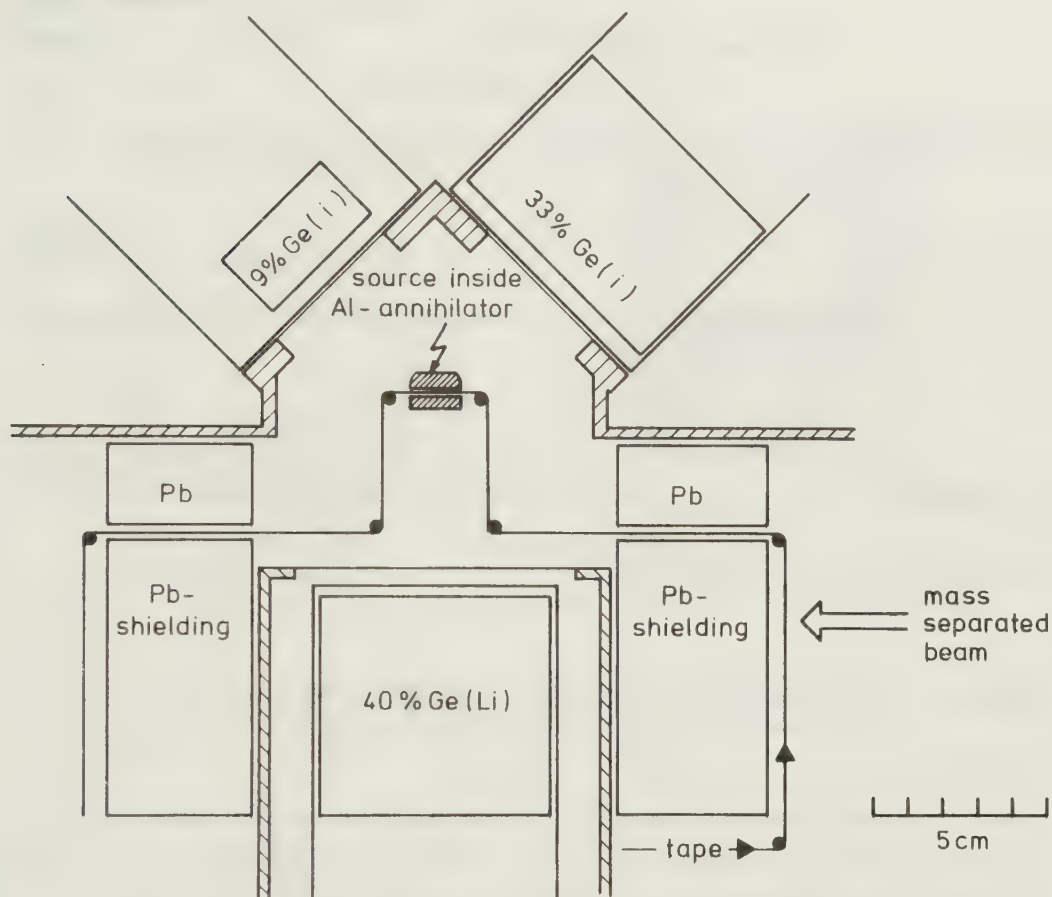


Figure 7. Experimental setup in 90 degrees geometry with annihilator to measure γ - γ -coincidences and Q_{EC} values.

This geometry and the rather large source-detector distance were chosen to reduce detector-to-detector scattering and multiple hits ('summing'). The source was sandwiched between two 5 mm aluminium plates. These annihilators are thick enough to stop the positrons (endpoint energy 3.2 MeV) but thin enough not to disturb the low energy part of the gamma spectrum too much. Thus the 511 keV annihilation quanta originate from the same point-like source as the gamma radiation.

This setup was used to measure gamma singles in the multispectrum analysis, the Q_{EC} values, by a determination of the $\beta^+ / (\beta^+ + EC)$ ratios, and coincidences for the most intense gamma transitions.

2. A large volume Ge(i) detector and a 'X-ray' intrinsic germanium detector in a close 180° geometry (Fig. 8) in order to gain statistics for the coincidence data, and thus detect weak transitions in the decay scheme.

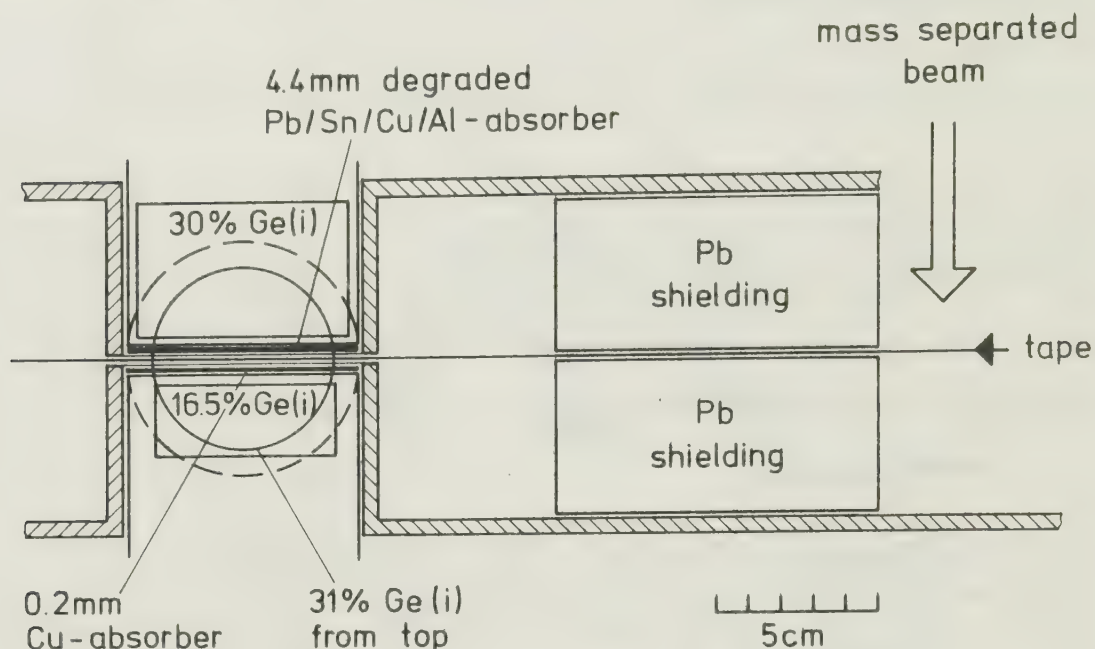


Figure 8. Experimental setup in 180 degrees geometry with a third Ge detector mounted from top at a distance of $\cong 5$ cm from the source

As this setup favours summing the X-ray detector was equipped with a 0.2 mm copper absorber to reduce the number of X-rays. Similarly the large volume Ge(i) detector was shielded by a graded absorber (0.1 mm Al, 0.1 mm Cu, 1 mm Sn, 2 mm Pb, 1 mm Sn, 0.1 mm Cu, and 0.1 mm Al) in order to reduce the low energy gamma lines of high intensity.

3. A mini-orange beta spectrometer with permanent magnets with a cooled silicon surface barrier detector in the focal plane (see ref. [34]) opposite to a γ X Ge(i) detector (Fig. 9).

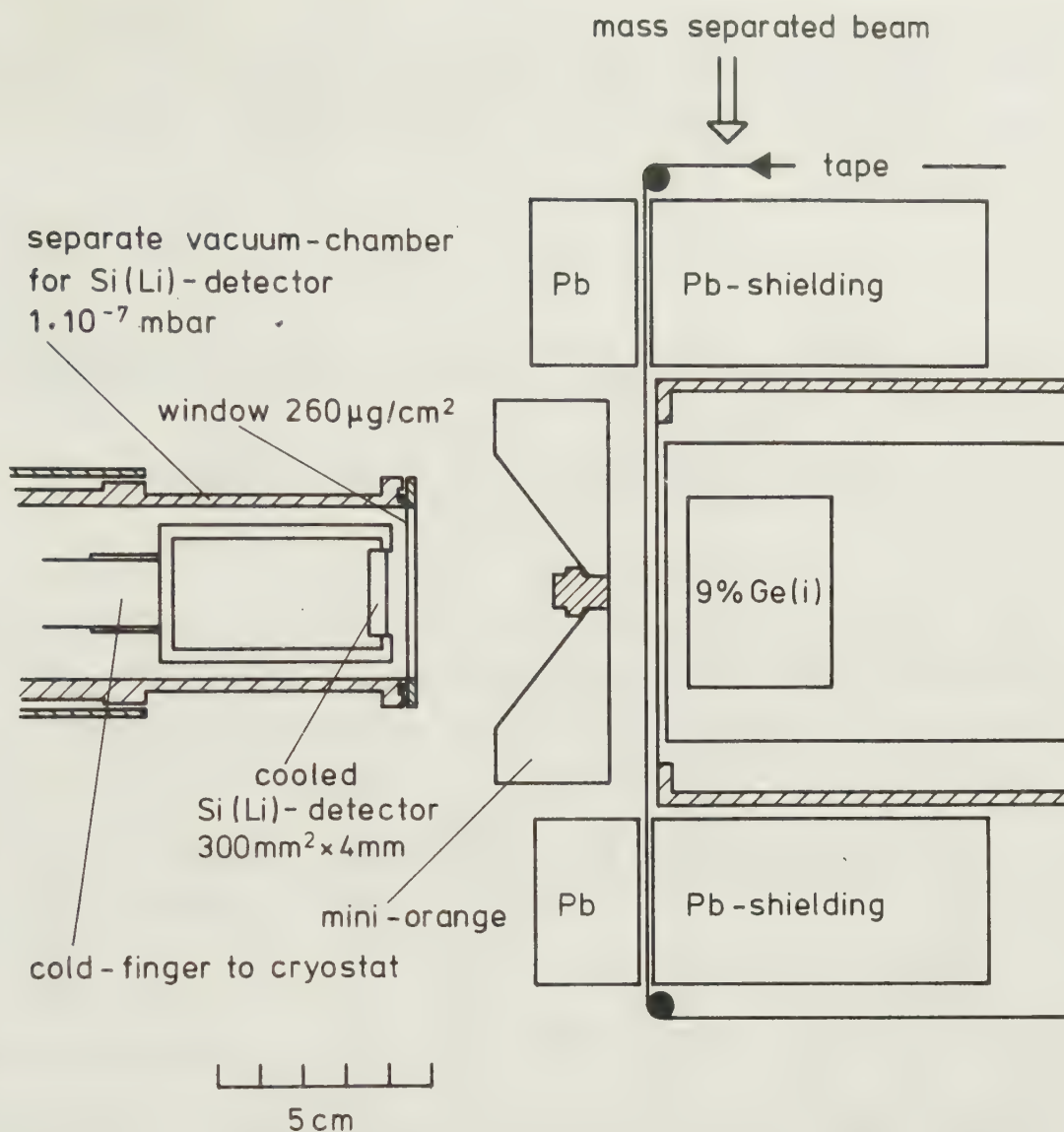


Figure 9. Experimental setup of the mini-orange type β -spectrometer with a γ -X-detector for measuring conversion coefficients and e^- - γ -coincidences

This setup was used to measure conversion electrons of the low energy gamma transitions and electron-gamma coincidences, and thus to obtain information on the multiplicities of the transitions.

The gamma detector efficiencies were determined by use of absolutely calibrated mixed gamma sources mounted in the counting position. The transmission curve and resolution of the mini-orange beta spectrometer was measured on-line with transitions of known intensities and multiplicities.

5.0 Experimental Results: ^{110}Sn , ^{108}Sn , ^{106}Sn

5.1 The Isotope ^{110}Sn

Our discussion of the decay properties of even neutron-deficient tin nuclei begins with ^{110}Sn . The relevant data are taken from ref. [36]. The nucleus ^{110}Sn decays with a groundstate Q_{EC} value of 560 ± 35 keV and a half-life of 4.1 h to an excited 1^+ state in ^{110}In at an energy of 238 keV. Thus the log ft value for this decay is 3.4.

5.2 The Isotope ^{108}Sn

The ^{108}Sn nuclei were produced by the $^{58}_{28}\text{Ni} (^{58}_{28}\text{Ni}, 6p2n) ^{108}_{50}\text{Sn}$ reaction. Our measurements reproduce the results of earlier work (refs. [8,37]). We find a decay to three 1^+ states in ^{108}In at excitation energies 1161.8 keV (relative feeding 4 %), 669.0 keV (80 %), and 272.7 keV (11 %), respectively. The log ft values to these states are 4.42(4), 3.52(3), and ≥ 4.8 , respectively. The log ft value corresponding to the sum of the strength of the individual transitions is 3.45(5); the averaged 1^+ state energy - weighted by the strength - is 0.7 MeV. The relevant expressions to deduce these results are given in chapter 8.2. The half-life of ^{108}Sn was re-determined to 623(10) s, and the Q_{EC} value re-determined to be 2059(25) keV.

5.3 The Isotope ^{106}Sn

The ^{106}Sn nuclei were produced via the $^{58}_{28}\text{Ni} (^{58}_{28}\text{Ni}, 6p4n) ^{106}_{50}\text{Sn}$ reaction. From

our gamma singles and gamma-gamma coincidence data we derive the decay scheme as shown in Fig. 11.

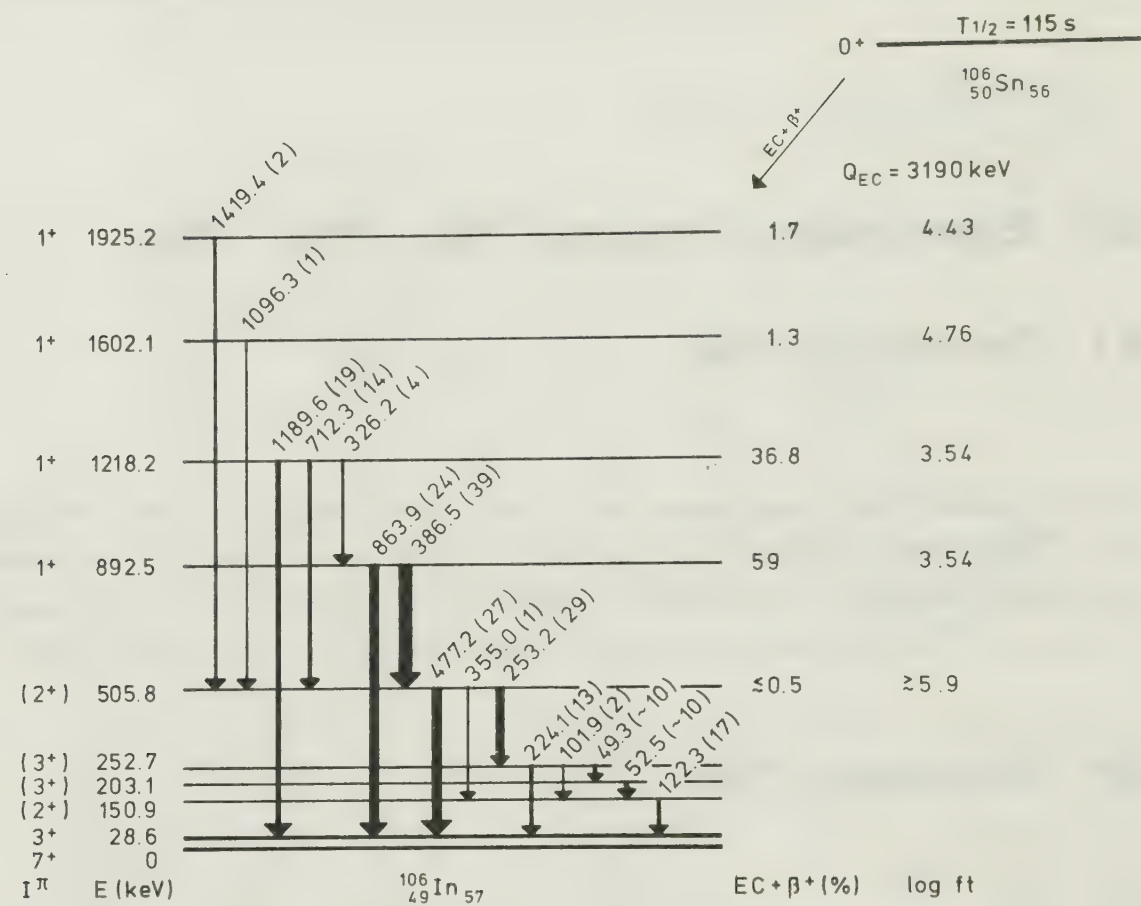


Figure 11. Decay scheme of ^{106}Sn

It differs from that proposed by the authors of ref. [38] with respect to the position of the 1096.3 keV and 1419.4 keV gamma transitions. Our assignment is unambiguous for the following reasons: As can be seen from Fig. 12, there is a clear coincidence between these two lines and those at 477.2 and 253.2 keV, but none with the lines at 863.9 and 386.5 keV. Therefore these two lines have to be placed on top of the level at 505.8 keV, not the one at 892.5 keV.

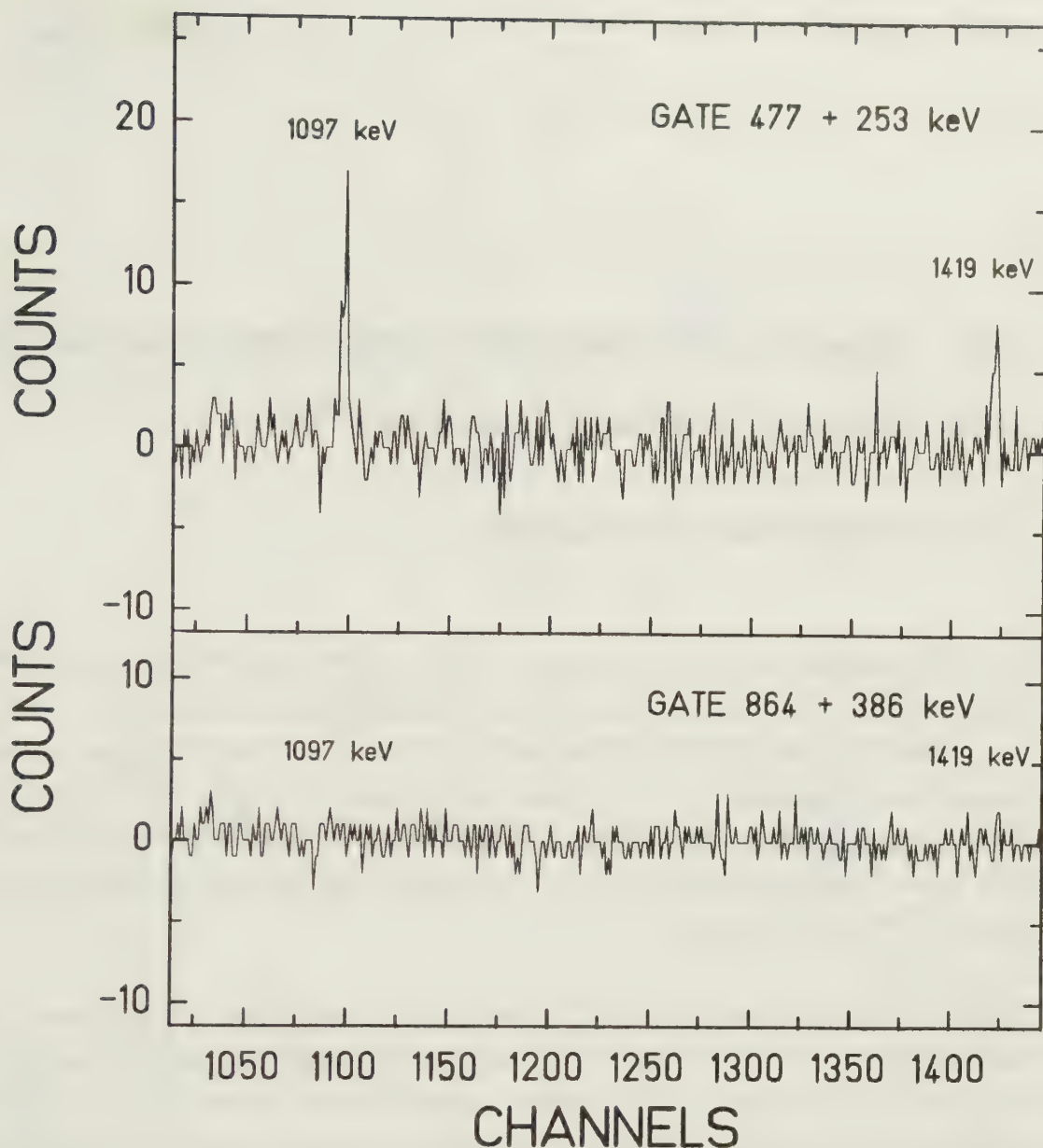


Figure 12. Coincidence spectra of ^{106}Sn illustrating the position of the lines at 1096.3 keV and 1419.4 keV in the decay scheme, see also text and Fig. 11.

With a half-life of 115(5) s and a Q_{EC} value of 3190(60) keV we obtain log ft values of 4.43(10), 4.76(8), 3.54(5), and 3.54(5) for the four 1^+ states in ^{106}In at 1925.2 keV, 1602.1 keV, 1218.2 keV, and 892.5 keV, respectively. Thus the overall log ft value (see chapter 5.2) for the $^{106}\text{Sn} \rightarrow ^{106}\text{In}$ beta decay is 3.24(5), and the averaged 1^+ state excitation energy is 1.1 MeV.

6.0 Experimental Results: Decay Properties of the New Neutron-Deficient Nucleus ^{104}Sn

6.1 Identification and Halflife

The ^{104}Sn nuclei were produced by the $^{50}_{24}\text{Cr} (^{58}_{28}\text{Ni}, 2p2n) ^{104}_{50}\text{Sn}$ reaction. The mass 104 beam from the mass separator was collected on the tape, and sources were transported regularly to the counting position. The cycle time of the tape transport system was set initially to 120 s to optimize the detection of the ^{104}In activity. Introducing foils of different thickness ('degraders') in front of the ^{50}Cr target the incident beam energy was varied in order to optimize to mass 104 production with a known ^{104}In gamma line.

A first hint for the new isotope ^{104}Sn was an unknown γ -line at 132.6 keV in the separated mass 104 activity which decayed with a considerably shorter halflife than the known $A = 104$ isobars. This halflife was measured to be (21 ± 1) s, relevant data are shown in Fig. 13. In order to optimize for this new activity the cycle time of the tape transport system was then set to 40 s.

The energies of the gamma lines assigned to the decay of ^{104}Sn are listed in Table 3, together with their relative intensities, halflives, and coincidence relations. The new transitions were found to be coincident both with indium X-rays and 511 keV annihilation radiation. An example is shown in Fig. 14. Therefore these transitions are ascribed to the decay of ^{104}Sn , and not of an isomer of ^{104}In .

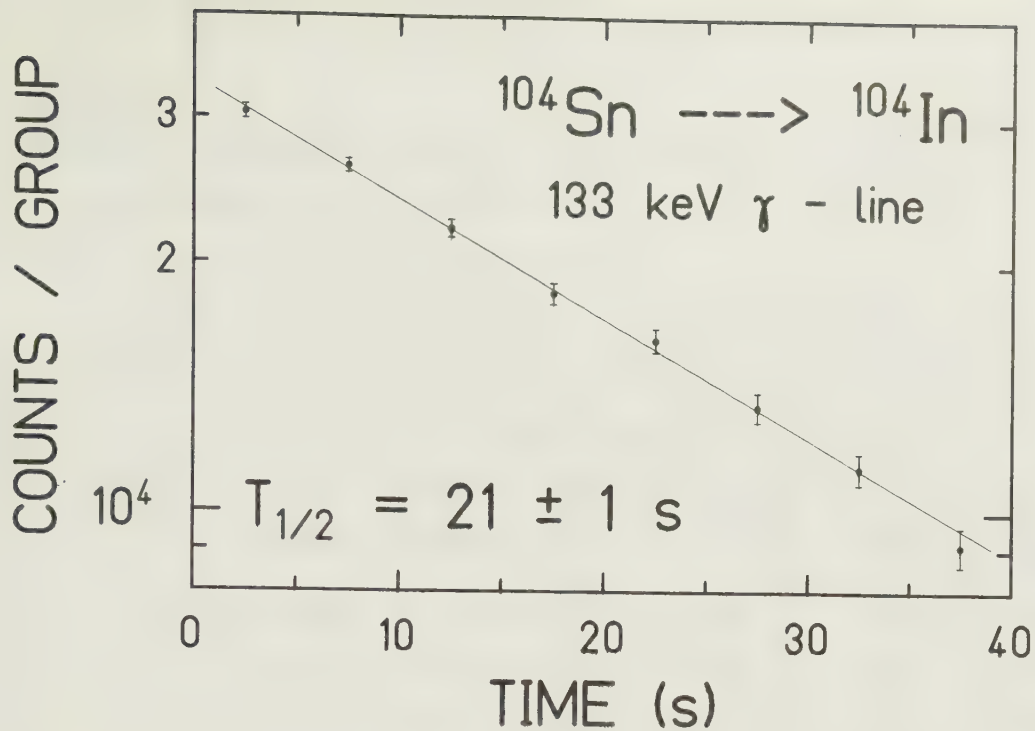


Figure 13. Decay curve of ^{104}Sn recorded for the 133 keV γ -line during 806 cycles of 40 s. The experimental points are shown together with the results of a least-square fit procedure

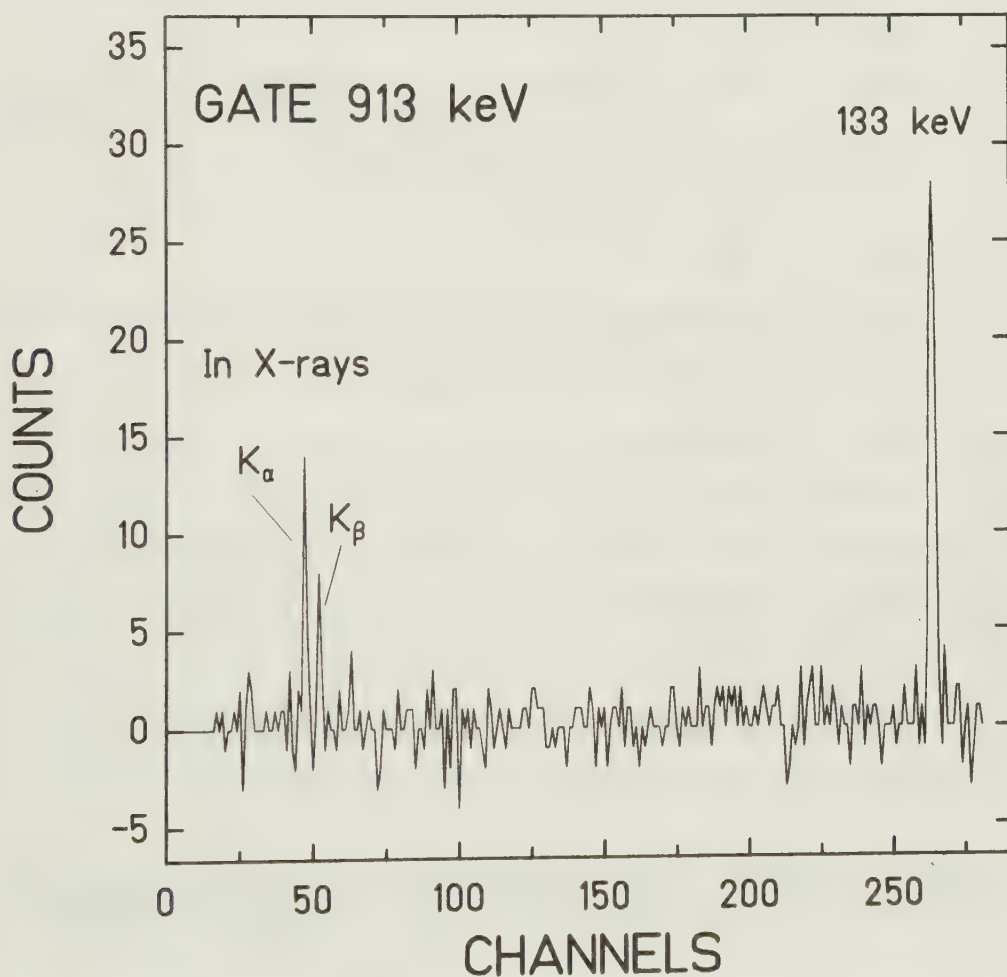


Figure 14. Coincidence spectrum of ^{104}Sn proving the assignment to the decay of ^{104}Sn by In-X-ray coincidences

E_{γ}	I_{γ}	coincident γ -lines
93.4(1) 93.5(2)	12(1)	148.1, 154.7, 342.3, 401.2, 703.5, 894.9, 511
132.6(1)	100	401.2, 703.5, 894.9, 912.6, 1156, 1215.3, 1407.3, 511
148.1(1)	15(1)	93.4, 154.7, 342.3, 401.2, 703.5, 894.9, 511
154.7(1)	10(1)	93.4, 148.1, 342.3, 401.2, 703.5, 894.9, 511
169.9(2)	1.5(3)	342.3, 511
217.4(2)	4(1)	342.3, 401.2, 511
302.8(2)	8(1)	342.3, 401.2, 511
342.3(2)	22(2)	93.4, 132.6, 148.1, 154.7, 169.9, 217.4, 302.8, 401.2, 703.5, 894.9, 511
401.2(2)	29(3)	93.4, 132.6, 148.1, 154.7, 342.3, 511
512 (1)	~ 12	
644.6(3)	19(2)	401.2, 511
703.5(3)	14(2)	93.4, 132.6, 148.1, 154.7, 342.3, 511
894.9(4)	15(2)	93.4, 132.6, 148.1, 154.7, 342.3, 511
912.6(4)	75(8)	132.6, 511
1045 (1)	≤ 2.5	
1156 (1)	~ 6	132.6
1215.3(5)	15(3)	132.6, 511
1273 (1)	~ 5	132.6
1407.3(5)	27(4)	132.6, 511

Table 3: Measured energies, relative intensities and coincidence relations for all γ -rays accompanying the decay of ^{104}Sn .

One exception is the transition at 93.5 keV which is due to the decay of an isomer in ^{104}In . Its half-life was deduced from the decay curve of the corresponding conversion electrons to be $(15.7 \pm 0.5) \text{ s}$ (see Fig. 15).

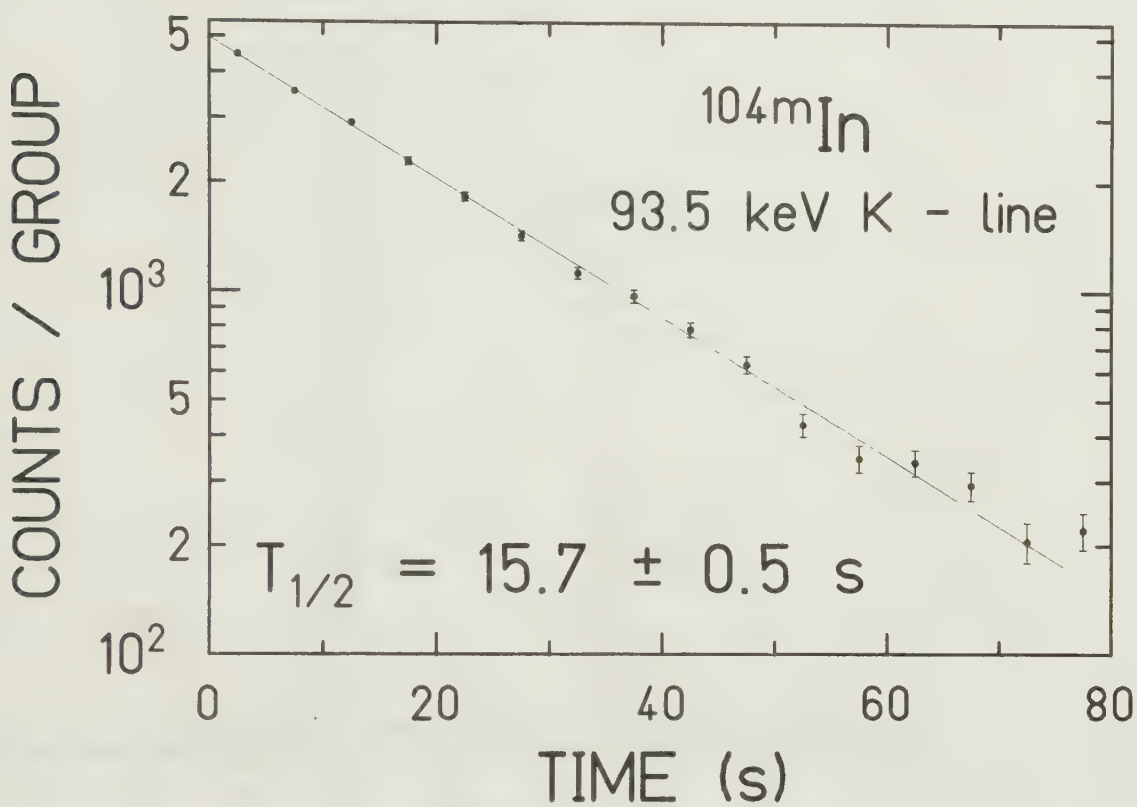


Figure 15. Decay curve for the isomer in ^{104}In measured for the K-electron line of the 94 keV transition during 28 cycles of 80 s. The experimental points are shown together with the results of a least-square fit procedure.

The unambiguous proof for the assignment of this activity to an ^{104}In isomer is illustrated in Fig. 16. It shows part of the conversion electron spectrum for two different operating modes of the FEBIAD ion source. A spectrum for the standard release mode is compared to one obtained in the bunched release mode, optimized to collection of the indium activity (hatched lines). As can be seen the ^{104m}In K and L lines are reduced somewhat in the bunched released mode, but the ^{104}Cd and ^{104}Sn lines are completely suppressed. For reduction factors see Table 1.

6.2 Level Energies

As shown in Fig. 17 the strong 132.6 keV gamma line is in coincidence with transi-

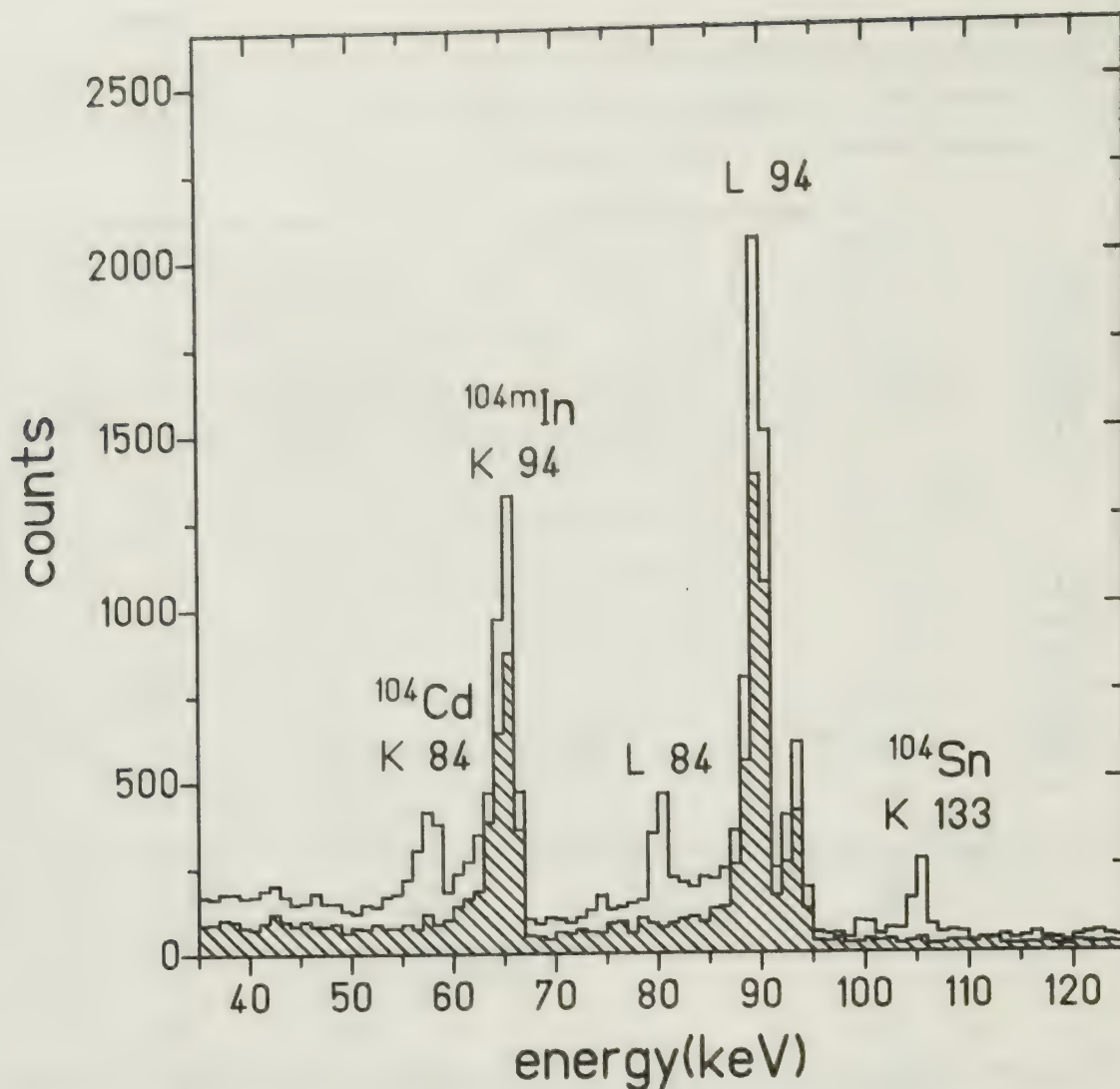


Figure 16. Conversion electron spectra measured in DC and bunched mode (hatched), leading to the assignment of the transition at 94 keV to ^{104}In , see also text.

tions of 401.2 keV, 703.5 keV, 894.9 keV, 912.6 keV, 1156 keV, 1215.3 keV, 1273 keV, and 1407.3 keV. These transitions depopulate the levels at 1138.8 keV, 1382 keV, 1441.5 keV, and 1633.5 keV. Another cascade depopulating these levels is the one by 342.3 keV, 154.7 keV, 148.1 keV, and 93.4 keV, via the levels at 738.1 keV, 396.3 keV, 241.5 keV, and 93.4 keV; this information is derived from the coincidence spectrum shown in Fig. 18.

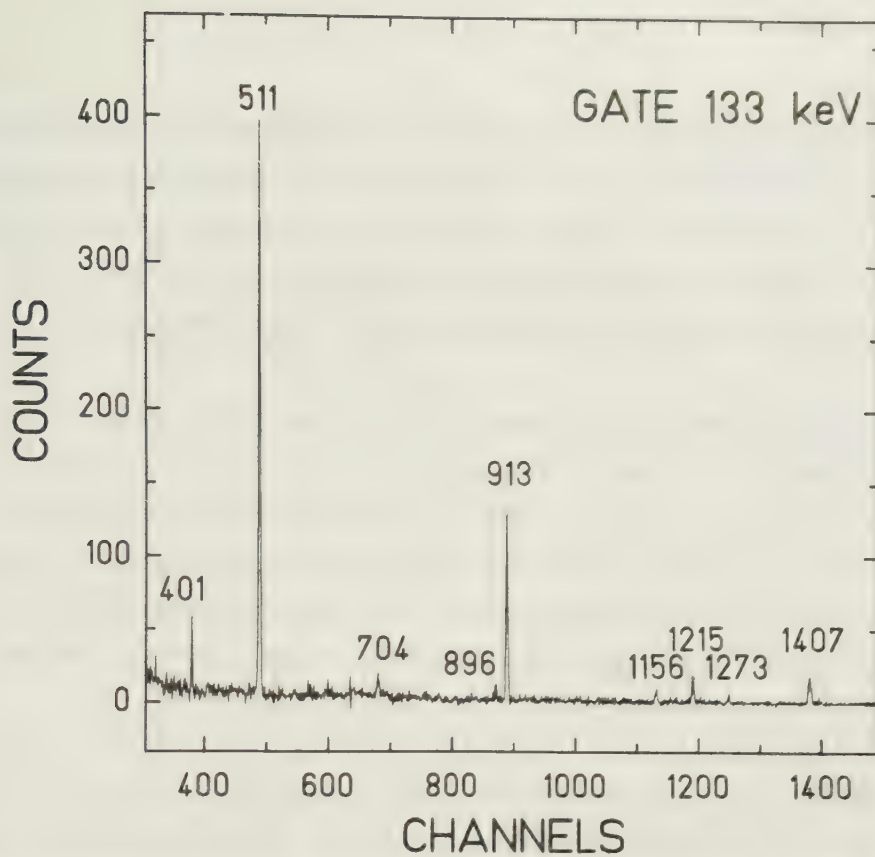


Figure 17. Coincidence spectrum of ^{104}Sn gated on the strongest γ -line at 133 keV

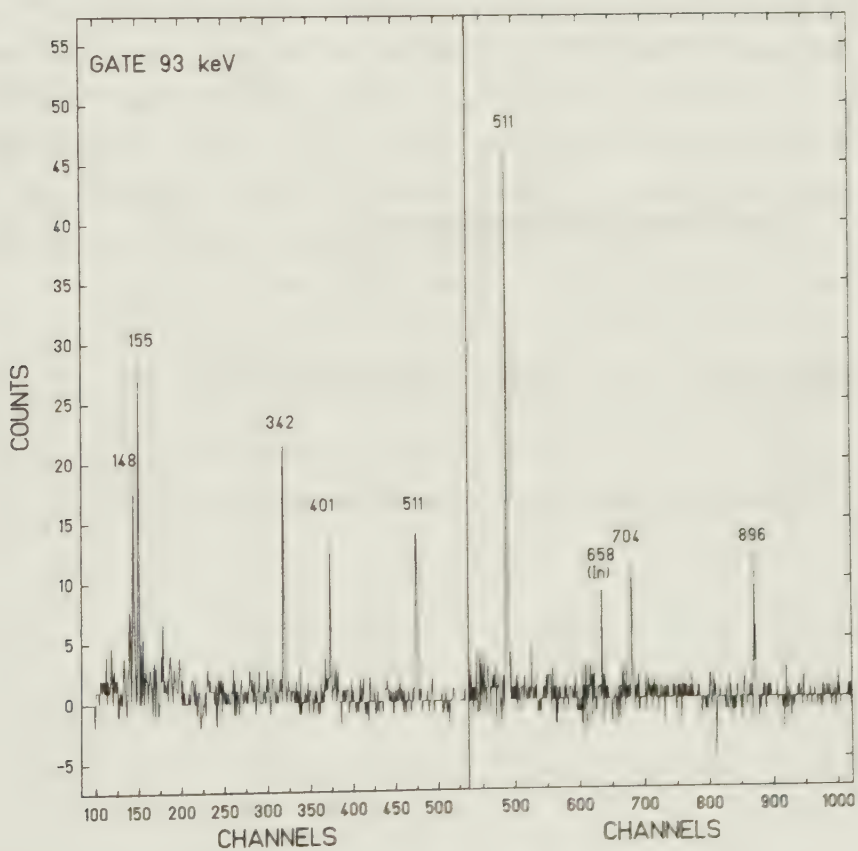


Figure 18. Coincidence spectrum of ^{104}Sn gated on the γ -line at 93 keV

The ordering of the 148.1 keV and 154.7 keV transitions is not completely unambiguous; the present choice is based on a comparison of intensities in the gated spectra. In addition we find a line at 644.6 keV, in coincidence with 401.2 keV depopulating the level at 738.1 keV. A coincidence of 302.8 keV and 169.9 keV with 342.3 keV shows that these two lines come down from the level at 396.3 keV

The rather strong coincidence between the lines at 132.6 keV and 401.2 keV gives rise to the assumption that there is a transition of 512 keV between the levels at 738.1 keV and 226.1 keV. This is confirmed by the following observation: The intensity of the line at 511 keV is higher in the spectrum gated by 401.2 keV than in the one gated by 912.6 keV the spectra being normalized to equal intensities of the gating lines; from such a procedure one would expect identical intensities for the 511 keV transitions if the transition at 512 keV were not there.

As the intensity balance normalized to the 132.6 keV transition does not show a side feeding into the levels at 738.1 keV and below, the intensities are normalized to add up to 100 % in the upper four levels at 1633.5, 1441.5, 1382, and 1138.8 keV. Corrections due to gamma-gamma angular correlations are negligible. The anisotropies are small, because at least one M1 transition and low spin values are involved in the strong cascades. Summing of strong gamma transitions is small in the 90° geometry because of the low efficiencies of the detectors and in the 180° geometry because of the absorbers used. These estimates are supported by the weak $133 \text{ keV} + 912 \text{ keV} = 1045 \text{ keV}$ transition observed and the non-observation of sum lines with 511 keV annihilation quanta in the data.

These arguments lead us to the decay scheme shown in Fig. 19.

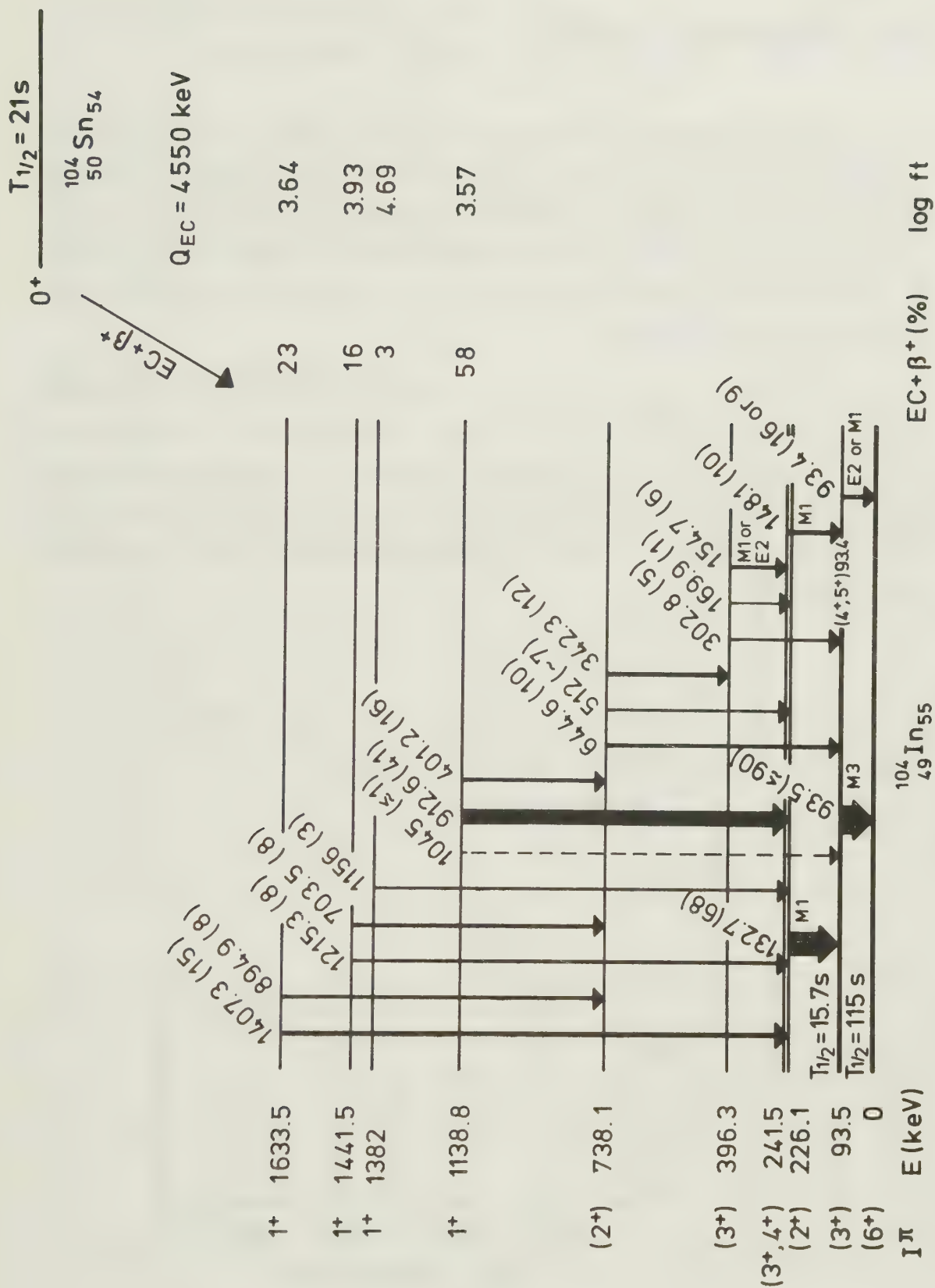


Figure 19. Decay scheme of ^{104}Sn

6.3 Groundstate Q-Value

The Q_{EC} -value was determined from the measured $\beta^+ / (\beta^+ + EC)$ ratio for the 1139 keV level, and a comparison to calculated ratios (see ref. [39]) which depend on the beta endpoint energy. The measurement was performed with the source inside the aluminium annihilator as described in chapter 3 in order to assure that the 511 keV annihilation quanta originate from the same more or less 'pointlike' source volume as the gamma radiation.

The $\beta^+ / (\beta^+ + EC)$ ratio is deduced for the 1139 keV level by comparing the intensity of this line in the spectrum gated by 511 keV to its 'single intensity'. Using gamma-gamma coincidence data it was verified that this ratio is not modified by feeding from higher-lying states. The experimental $\beta^+ / (\beta^+ + EC)$ ratio is determined to be (0.71 ± 0.07) . The theoretical values, dependent on the beta endpoint energies are shown in Fig. 20.

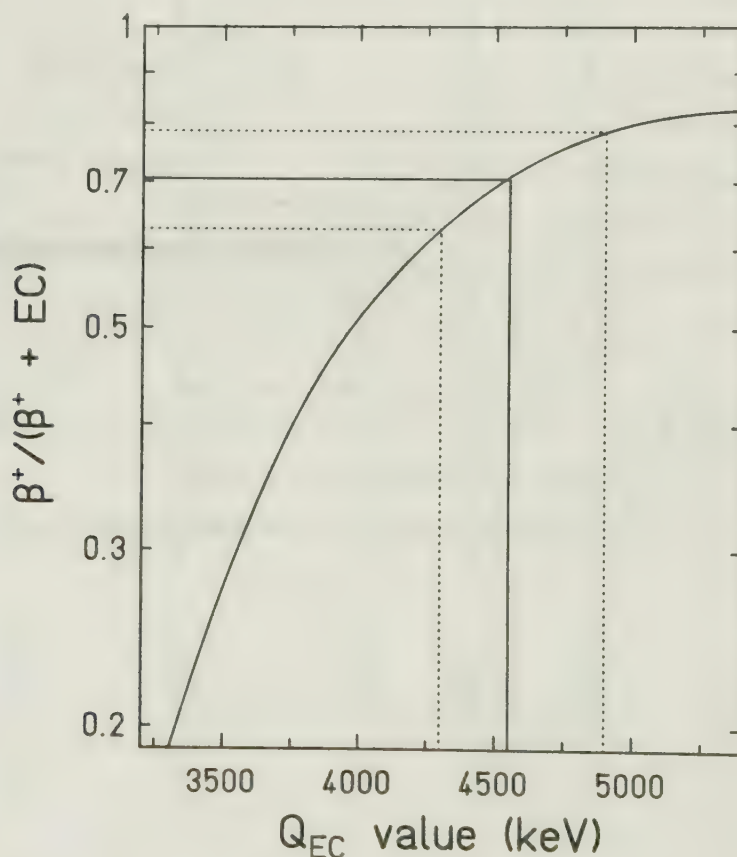


Figure 20. Theoretical curve for the Q-value determination showing the ratio $\beta^+ / (\beta^+ + EC)$ depending from the Q-value. The full line shows our measured value with the errors indicated in dotted lines.

From this comparison we deduce the beta endpoint energy for the beta decay to the level at 1139 keV to be $(2390 \pm 350) \text{ keV}$. Thus the Q_{EC} -value is $(4550 \pm 350) \text{ keV}$.

This result was compared to a similar measurement performed previously for the 1139 keV and 1634 keV levels (see ref. [8]); actually a double ratio for these two levels was determined in this case. The result, $Q_{\text{EC}} = (4000 \pm 650) \text{ keV}$ is in agreement with the value quoted above.

6.4 Spin Assignments

From the electron spectrometer measurements we deduce the multiplicities for several low energy transitions. Experimental and theoretical values for the conversion coefficients are given in Tables 4 and 5.

E_γ [keV]	α_K (exp.)	α_K (theor.)		
		E1	M1	E2
132.6	0.20 ± 0.03	0.07	0.20	0.44
148.1	0.17 ± 0.03	0.05	0.15	0.30
154.7	0.21 ± 0.07	0.04	0.13	0.27

Table 4: K-conversion coefficients of transitions accompanying the decay of ^{104}Sn ; theoretical values from ref. [40]

	exp.	M2	E3	M3	E4
α_K	50 ± 15	5.3	8.6	44	53
K/L	2.0 ± 0.6	5.3	0.84	2.7	0.26

Table 5: Conversion electron data for the 93.5 keV isomeric transition in ^{104}In ; theoretical values from ref [40]

For the transitions at 132.6 keV and 148.1 keV we find the multipolarity to be M1, whereas a distinction for the 154.7 keV transition between M1 and E2 is not possible. The K-conversion coefficient for the isomeric transition at 93.4 keV would not allow to distinguish between M3 and E4 multipolarity, but the K/L ratio excludes the E4 and proves the M3 assignment.

As the log ft values for the four levels fed in the beta decay at 1633.5 keV, 1441.5 keV, 1382 keV, and 1138.8 keV are as small as 3.6 to 4.7, we assume that these are 1^+ states populated in the $0^+ \rightarrow 1^+$ GT transition (this will be discussed in detail in chapter 8). These levels mainly decay to two states, one at 226.1 keV and, partially weaker, one at 738.1 keV. The intensity ratios suggest that these transitions have mainly M1 multipolarity. Therefore we assign 2^+ to these levels.

Due to the measured M1 multipolarity of the 132.6 keV transition we assign 3^+ to the level at 93.5 keV. The M3 multipolarity of the isomeric transition at 93.5 keV leads to spin 6^+ for the groundstate of ^{104}In . Experimental results obtained from collinear laser spectroscopy (see ref. [41]) suggest $I = 5$ or $I = 6$.

For the gamma transition at 93.4 keV the statistics of the data was not sufficient to distinguish between M1 and E2 multipolarity, therefore we assign either 4^+ or 5^+ to this level. The level at 241.5 keV should have spin-parity 3^+ or 4^+ , as the transition at 148.1 keV has M1 multipolarity. For the level at 396.3 keV we assume that the relatively strong transition at 342.3 keV has also M1 multipolarity and assign 3^+ to this level.

7.0 Discussion of Binding and Excitation Energies

Even nuclei near ^{100}Sn decay by fast $0^+ \rightarrow 1^+$ GT transitions. The one or several final states fed directly in the decay have a $(\pi g_{9/2}^{-1} \times \nu g_{7/2})_{1^+}$ component in their wave function which determines the GT beta transition strength.

In this section we will compare results from theoretical calculations with the following measured quantities: the groundstate to groundstate Q values, the center of gravity energy $E(1^+)$ of the 1^+ states, and the groundstate masses of nuclei linked to ^{104}Sn by alpha- or proton-radioactivity. The corresponding GT strength will be discussed in the following chapter.

A compilation of the experimental data is given in Table 6.

	$^{104}_{50}\text{Sn}_{54}$	$^{106}_{50}\text{Sn}_{56}$	$^{108}_{50}\text{Sn}_{58}$	$^{110}_{50}\text{Sn}_{60}$
$E_{1^+}(\text{MeV})$	1.38	1.1	0.7	0.3
$Q_{\text{EC}}(\text{MeV})$	4.55	3.19	2.059	0.58
log ft	3.20	3.24	3.45	3.4

Table 6: Compilation of experimental results for the neutron-deficient even tin isotopes. The energies of the 1^+ states and log ft values for the $^{104}, ^{106}, ^{108}\text{Sn}$ decays are averaged as described in the text.

7.1 Brief Description of the Models

Three model calculations are compared to experimental results for Q_{EC} values, average 1^+ state excitation energies and $\log ft$ values for the decay of neutron-deficient tin nuclei. Nuclear binding is calculated from a minimalization procedure of the potential energy.

Model I is a self-consistent Hartree-Fock-Bogolubov calculation for spherical nuclei. A Skyrme-type residual two-body interaction is used, and pairing correlations are treated by the full HFB method instead of the BCS approach. Details are given in ref. [42].

Model II is a macroscopic-microscopic hybrid calculation. The nuclear potential energy is expressed as the sum of a Möller-Nix type [43] liquid drop term, and a microscopic part. This latter term is calculated with a Woods-Saxon potential and parameters given in ref. [42], and accounts for the shell corrections calculated by the Strutinsky prescription, and for pairing of like nucleons. The calculations are first performed under the assumption of a spherical nuclear shape (Model II-sph.) and then by varying the nuclear deformation (Model II-def.).

Model III is the original Möller-Nix calculation (ref. [43]). It is identical in the liquid-drop macroscopic part with the Model II calculation, but uses a folded-Yukawa single-particle potential instead of the Woods-Saxon potential to calculate the microscopic correction terms.

7.2 Groundstate Q -Values for ^{110}Sn , ^{108}Sn , ^{106}Sn , ^{104}Sn

The experimental Q_{EC} values are plotted in Fig. 21. Also shown are the results of the model calculations. All three calculations reproduce the order of magnitude and the mass dependence quite well. Model II-def. is in best absolute agreement with the data.

The nuclear shape information deduced from the latter calculations are as follows:

1. The groundstates of the tin mother nuclei are found to be spherical.
2. The groundstates of ^{110}In through ^{104}In are slightly deformed, with deformation parameters β_2 ranging from 0.12 to 0.07, and β_4 close to zero. These findings are in agreement with results from collinear laser spectroscopy (see ref. [41]).
3. The 1^+ excited states fed in the beta decay are calculated to be almost spherical, with β_2 close to zero.

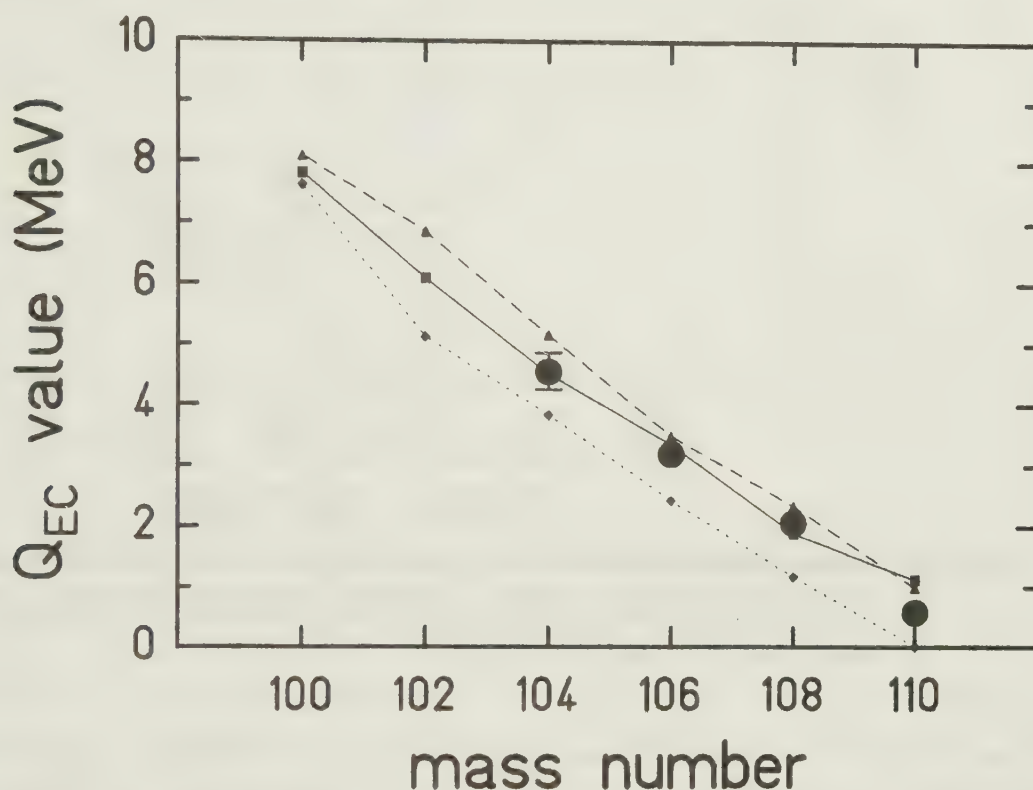


Figure 21. Comparison of experimental and theoretical Q -values of the light even tin isotopes. The dashed line shows the calculations from Model I, the full line from Model II-def., and the dotted line from Model III. For description of the models see text.

7.3 Center-of-Gravity Energies of 1^+ States

The averaged excitation energies of the 1^+ states in $^{110,108,106,104}\text{In}$ as deduced from the experiments are plotted in Fig. 22. The 'data point' for ^{100}In was deduced from a Pandya transformation to 'predict' the level structure of the particle-hole nucleus ^{100}In from the known levels of the particle-particle nucleus ^{92}Nb (see

ref. [44]). Also shown are the results according to Models 1 and II-def. Model III does not give excitation energies.

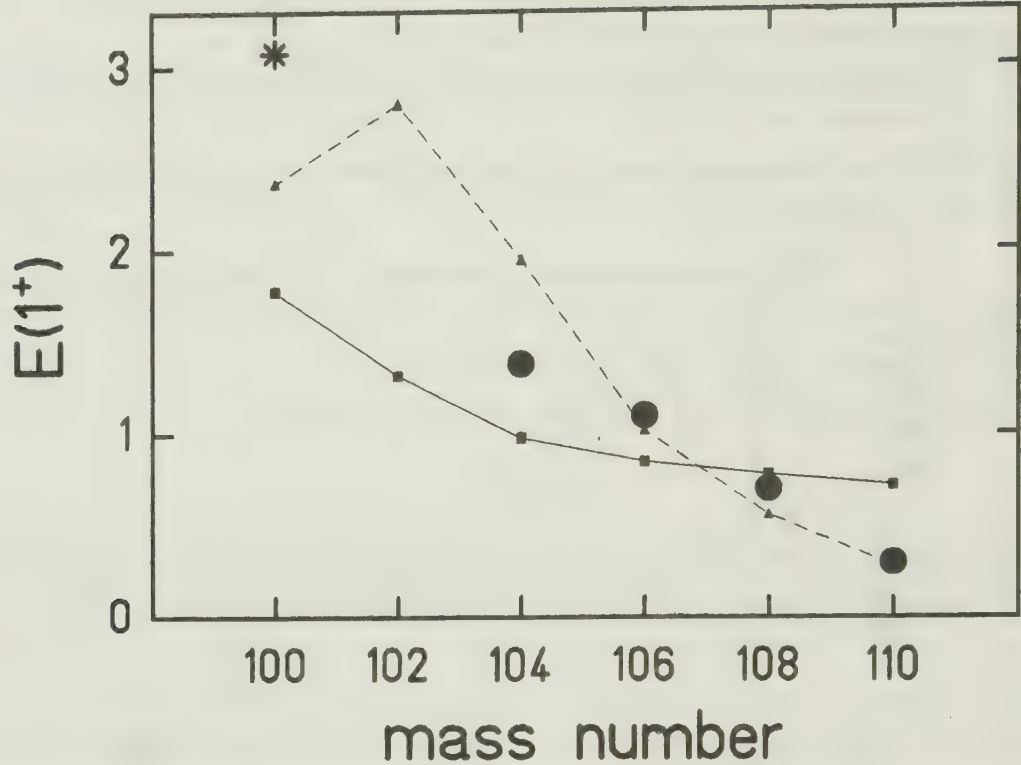


Figure 22. Comparison of weighted 1^+ state sum energies in MeV for the light even tin isotopes with calculated values. The dashed line represents Model I, the full line Model II-def. The asterisk shows the value for ^{100}In from ref. [44]. For description of the models see text.

None of the two models reproduces the data exactly. Since Model I is a calculation for spherical nuclei, and Model II-def. predicts the 1^+ states to be nearly spherical, the discrepancy between the two calculations for the lightest indium isotopes appears to be a systematical problem not yet understood.

7.4 Mass Excess Values for ^{108}Te , ^{109}I , ^{112}Xe , and ^{113}Cs

From the known mass excess value of ^{104}Cd (ref. [45]), the Q_{EC} value of ^{104}In (refs. [46,47]), and our result for the the Q_{EC} value of ^{104}Sn we deduce the mass excess of ^{104}Sn to be $(- 72.2 \pm 0.4)$ MeV. This value can then be combined with alpha-decay (ref. [48]) and proton-decay (ref. [49]) data to yield mass excess values

deduced for ^{108}Te , ^{112}Xe , ^{109}I , and ^{113}Cs , the last two nuclei lying beyond the proton drip line (see Fig. 23).

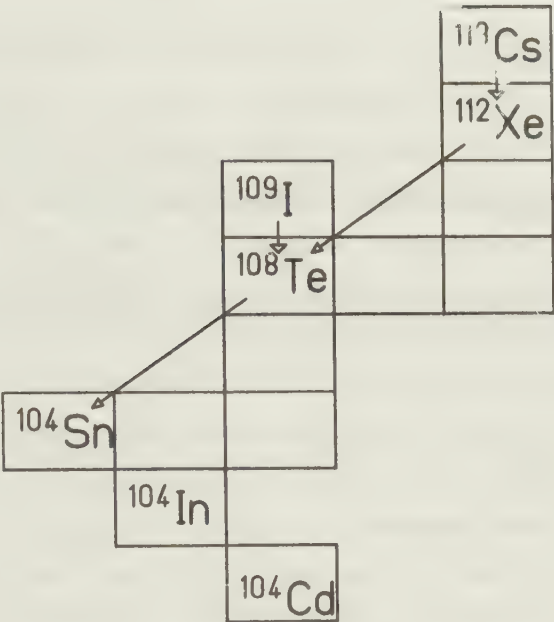


Figure 23. Illustration for the link to different masses

In these calculations we have assumed that the particle decays occur from and lead to the corresponding groundstates. The results are given in Table 7.

nucleus	^{104}Sn	^{108}Te	^{109}I	^{112}Xe	^{113}Cs
ME [MeV]	-72.21	-66.34	-58.23	-60.59	-52.33

Table 7: Mass excess values for different proton-rich nuclei, the error is ± 400 keV for all the cases

Since the mass excess value of ^{104}Sn is subject to a large error, the errors for the mass excess values lie around ± 400 keV each. Therefore it is not yet meaningful to compare these numbers to detailed theoretical calculations.

7.5 Strength of the $Z = 50$ Proton Shell

As discussed earlier (see ref. [8]), the $Z = 50$ proton-shell strength can be expressed by the difference of the α -decay energies: $\Delta Q_\alpha(N) = Q_\alpha({}^A_{52}\text{Te}_{N+1}) - Q_\alpha({}^{A-2}_{50}\text{Sn}_{N+1})$. It is expected that the double shell closure in ${}^{100}\text{Sn}$ should manifest itself through an increasing ΔQ_α value when approaching ${}^{100}\text{Sn}$ (such a mutual support of the shell strength was discussed for heavy nuclei in ref. [50]).

The ΔQ_α values for neutron numbers above 53 are shown in Fig. 24, adding new points (data mostly from ref. [51]) to those presented in ref. [8]. The tendency of decreasing ΔQ_α values with departure from $N = 50$ seems to show up. However, for higher N these values begin to increase again, reaching maxima at $N = 64$ and 66 . For $N = 64$, in analogy to $Z = 64$, we can expect a subshell closure, so that the relatively high ΔQ_α value could correspond to the mutual shell-strength support mentioned above. An energy gap at $N = 64$ is indeed obtained from Nilsson model calculations with parameters adjusted to reproduce other experimental data in this region of the nuclidic chart. The reason for the maximum of ΔQ_α at $N = 66$ is not clear.

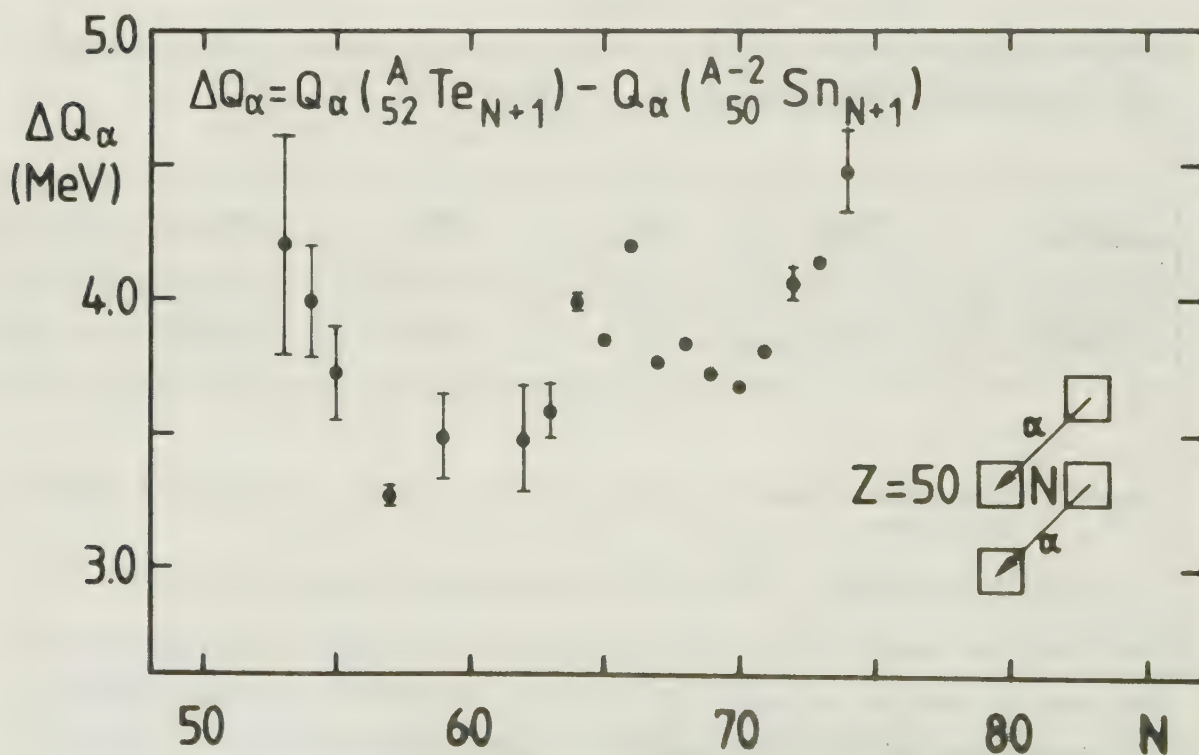


Figure 24. Estimate of the strength of the $Z = 50$ proton shell, as deduced from ΔQ_α values

8.0 The Gamow-Teller Beta Strength

8.1 Extreme Single Particle Model Considerations

The single particle level scheme for nuclei near ^{100}Sn is shown in Fig. 25.

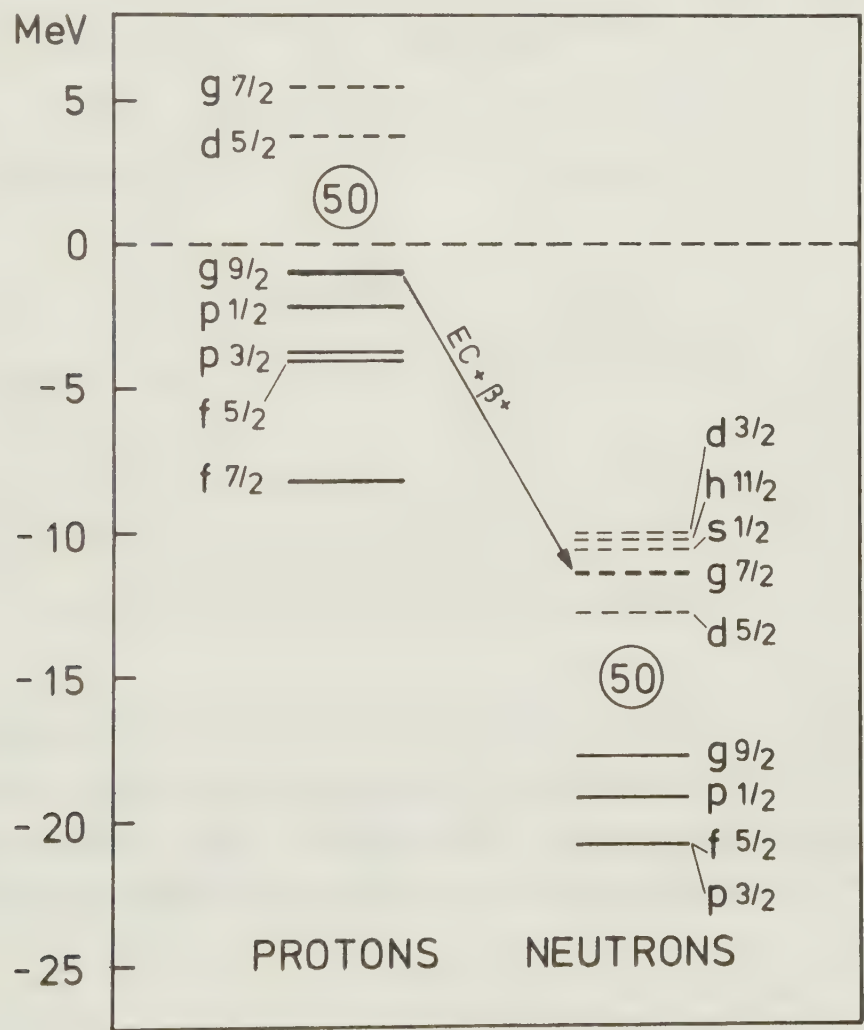


Figure 25. Theoretical shell model orbitals for ^{100}Sn The values are taken from ref. [52].

Without any residual interactions we expect only one route for the $^{100}_{50}\text{Sn}_{50} \rightarrow ^{100}_{49}\text{In}_{51}$ beta decay, namely the

$$|\pi g_{9/2}^{10}, O^+ > \rightarrow |\pi g_{9/2}^9 \nu g_{7/2}, 1^+ >$$

GT transition. In this case the notation corresponds to $^{90}_{40}\text{Zr}$ core, but this conclusion is independent of the question whether $^{88}_{38}\text{Sr}$ or $^{90}_{40}\text{Zr}$ is used as a core.

For the Sn isotopes heavier than ^{106}Sn this decay path is partially blocked by filling of the $\nu g_{7/2}$ orbital. Similarly, for nuclei with $40 \leq Z \leq 49$ and $50 \leq N \leq 56$ the strength is reduced because the $\pi g_{9/2}$ orbital is only partially filled.

The transition rate for beta decay is characterized by the ft value

$$ft = \frac{6160}{(g_A/g_V)^2 B_{\text{GT}}} s$$

(see ref. [14] as for all following definitions) where the coupling constant ratio has the free nucleon value, $(g_A/g_V) = -1.263$ and $B(\text{GT})$ is the square of a nuclear matrix element

$$B_{\text{GT}} = \sum_{\mu} | \langle f | \sum_k t_{\pm}(k) \sigma_{\mu}(k) | i \rangle |^2$$

For nuclei with $40 \leq Z \leq 49$, $50 \leq N \leq 56$, and n protons in the $\pi g_{9/2}$ orbital the $B(\text{GT})$ is

$$B_{\text{sp}}(\text{GT}) = n \frac{4l}{2l+1}, \quad l=4$$

Thus the ft value should be inversely proportional to n, and the experimental values for the $N = 50$ isotones tend to confirm this (see ref. [53]). For the $^{100-106}_{50}\text{Sn}$ isotopes we derive $B_{\text{sp}}(\text{GT}) = 160/9$ and $\log ft = 2.34$. Compared with the typical ft values of superallowed beta decay, $\log ft \cong 3.5$, these are very fast transitions, indeed.

8.2 Spreading of the Beta Strength to Several Final 1^+ States

Because of residual nucleon-nucleon interaction it is to be expected that the shell model configuration

$$| \pi g_{9/2}^n \nu g_{7/2}^{n-1}, 1^+ >$$

is distributed over several final 1^+ states, and it is the sum of strength to all these states that has to be compared to $B_{sp}(GT)$. The experimental information on this spreading of the GT decay strength is compiled in Fig. 26.

In order to achieve the comparison between theory and experiment we calculate average excitation energies of the 1^+ states (see chapter 7.3)

$$E_{1^+} = \frac{\sum_i E_i (\frac{1}{ft})_i}{\sum_i (\frac{1}{ft})_i}$$

and a summed GT strength from

$$\frac{1}{ft} = \sum_i (\frac{1}{ft})_i$$

Since we have an experimental threshold, and do not detect weakly populated ($\leq 1\%$ branching) 1^+ final states, we have to estimate how much strength would be missed in these measurements.

Our consideration is based on a theoretical calculation for ^{112}In (see ref. [54]). Neutron-quasiparticle proton-hole multiplet states, in particular the 1^+ groundstate, are coupled to quadrupole-phonon excitations of the even core. The wave function is written as

$$| J > = \sum d(NRI; J) | (NR) \otimes (nlj_\nu \otimes n'l'j_\pi; J >$$

Here n, l, j are the usual quantum numbers of shell model orbitals (see ref. [55]), N is the number and R the angular momentum of the quadrupole phonons and $d(NRI; J)$ are angular momentum coupling coefficients.

Figure 26. **Compilation of the experimental information** on the spreading of 1^+ states in odd-odd nuclei, and on the energies of core excitations of even-even nuclei with $N = 50$ and $Z = 50$. This figure is an updated version of the one given in ref. [56]

For the ^{112}In groundstate the main components of the wave function are calculated to be

$$\begin{aligned} |1^+ > = & +0.85 | (0,0) \otimes (\pi g_{9/2}^{-1} \otimes \nu g_{7/2})_1 ; 1^+ > \\ & -0.33 | (1,2) \otimes (\pi g_{9/2}^{-1} \otimes \nu g_{7/2})_2 ; 1^+ > \\ & +0.24 | (1,2) \otimes (\pi g_{9/2}^{-1} \otimes \nu g_{7/2})_3 ; 1^+ > \end{aligned}$$

The zero phonon component important for beta decay accounts for 72 % of the wave function, thus 28 % of the strength is missing.

It is not clear, however, whether these conclusions can be applied to the lighter indium isotopes, too. As can be seen from Fig. 26 the 2^+ core excitation energy remains more or less unchanged around 1.2 MeV. Since the number of valence neutrons decreases towards ^{100}Sn , one might expect that the particle-hole core coupling decreases also. Calculations are needed to confirm this expectation.

8.3 Quenching of the Summed Beta Strength

In Fig. 27 we compare $B_{\text{sp}}(\text{GT})$ and the corresponding log ft values with the experimentally observed GT transition strength. Obviously there is a retardation mechanism which we quantify by defining a 'hindrance factor' $h = B_{\text{sp}}(\text{GT}) / B_{\text{exp}}(\text{GT})$. Typical hindrance factors are large, and in the range $6 \leq h \leq 14$.

These retardation effects have stimulated various theoretical investigations recently. Actually the problem is not new. The quenching of the magnetic moments and magnetic transition probabilities in nuclei as compared to free nucleon values is known since long time, and the 'missing GT strength' in (p,n) reaction studies became obvious after 200 - 300 MeV proton machines became available.

The main line of theoretical reasoning is as follows: Nuclear structure calculations in a truncated configuration space always result in a re-normalization of free nucleon operators and the corresponding matrix elements. One possibility to remedy this problem is to use effective operators, with empirically deduced 'quenched' coupling constants and unmodified wave functions; another is to consider a few additional

components in the wave functions explicitly without renormalizing the operators. In first order perturbation theory both methods are equivalent.

An early (1954) example is the Arima and Horie analysis of magnetic moments (see ref. [57]). 'Higher order' effects are treated by a combination of the two procedures: First order processes, in particular the admixture of the 1^+ dipole states, are treated explicitly, and higher order phenomena are taken into account by the use of 'effective coupling' constants. These are determined from 'general experience'.

In our case we apply the following approach; actually part of the published theoretical work was stimulated by and derived in close connection to our experimental investigations.

1. Starting point is the extreme single particle shell model, as described above, with $B_{sp}(GT) = 160/9$ for the ^ASn isotopes, and $(g_A/g_V) = -1.263$, with g_A and g_V being the usual coupling constants as determined for the beta decay of the free neutron. We assume an empty $vg_{7/2}$ orbital for all the tin nuclei up to $A = 110$ (upper solid line in Fig. 27).
2. Next we correct for pairing as calculated by Dobaczewski (see ref. [42])

$$B_{ref}(GT) = \frac{160}{9} v_p^2 u_n^2$$

For the $^{100}\text{Sn} \rightarrow ^{100}\text{In}$ case the new reference values are

$$B_{ref}(GT) = 15.9, \quad [\log(ft)]_{ref} = 2.39$$

with $v_p^2(\pi g_{9/2}) = 0.92$ and $u_n^2(vg_{7/2}) = 0.97$ where v_p^2 describes the 'fulness' of the $\pi g_{9/2}$ orbital and u_n^2 the 'emptiness' of the $vg_{7/2}$ orbital.

As expected the influence of the pairing correlations is rather small for the doubly magic ^{100}Sn . According to theory the proton part of the wave functions does not vary appreciably for the heavier tin isotopes. However, the influence of the neutron pairing varies gradually from ^{100}Sn to ^{110}Sn . Therefore the theoretically predicted $B(GT)$ values are **not** constant for ^{100}Sn to ^{110}Sn , but decrease steadily with increasing mass. The calculated strength is indicated by the dashed-dotted line in Fig. 27.

3. Next we consider corrections for 'core polarization' in first order perturbation theory as discussed in connection with magnetic moments already by Arima and Horie (ref. [57]) for closed shell plus one nuclei. Since we are dealing with closed shell plus n nuclei, and $N \cong Z$, we have to consider additional first order contributions. Such calculations have been performed by Towner (ref. [14]) under the assumption of various two body residual interactions. According to Towner the hindrance factors for 'core polarization' are approximately $1.29 \leq h_c \leq 1.71$. The results are shown as dashed areas in Fig. 27.
4. Finally we have to consider all the higher order terms, i.e. the construction of an effective operator beyond first order perturbation theory, and the influence of additional degrees of freedom, the role of Δ -isobars included.

The role of the Δ -isobar admixtures was estimated by Bohr and Mottelson (ref. [49]). In principle this admixture is equivalent to the spin-orbit partner particle-hole type discussed earlier. Although the Δ -particle nucleon-hole excitation is $\cong 300$ MeV away the interaction is correspondingly strong. Estimates for the hindrance factor vary from $\cong 1.6$ (ref. [49]) to only $\cong 1.2$ (ref. [58]).

Following the lower estimate, other higher order terms have to be considered. 'Mesonic currents' will influence the orbital part of an effective GT one-body operator, as known from the analysis of magnetic moments. Many more components of the wave function than the spin-orbit partners considered will contribute in higher order perturbation theory. The influence of these is generally called 'tensor correlations'.

It is apparent from a comparison of experiment and theory (single particle plus pairing plus core polarization) that additional quenching mechanisms are at work. What is apparent from theory is that there is a large cancellation among the various 'higher order corrections'. In order to account for these Towner (ref. [14]) suggests to introduce an effective higher order hindrance factor $h_{ho} \cong 1.6$; This value is consistent with systematic studies of the (p,n) reactions to the GT states which find uniformly that only 50 - 60 % of the expected sum rule strength is observed.

In the case of the neutron-deficient tin nuclei this empirical factor $h_{ho} \cong 1.6$ is **not** sufficient to explain the data, we would rather need a factor around 4. The reason for this discrepancy is not understood at this point.

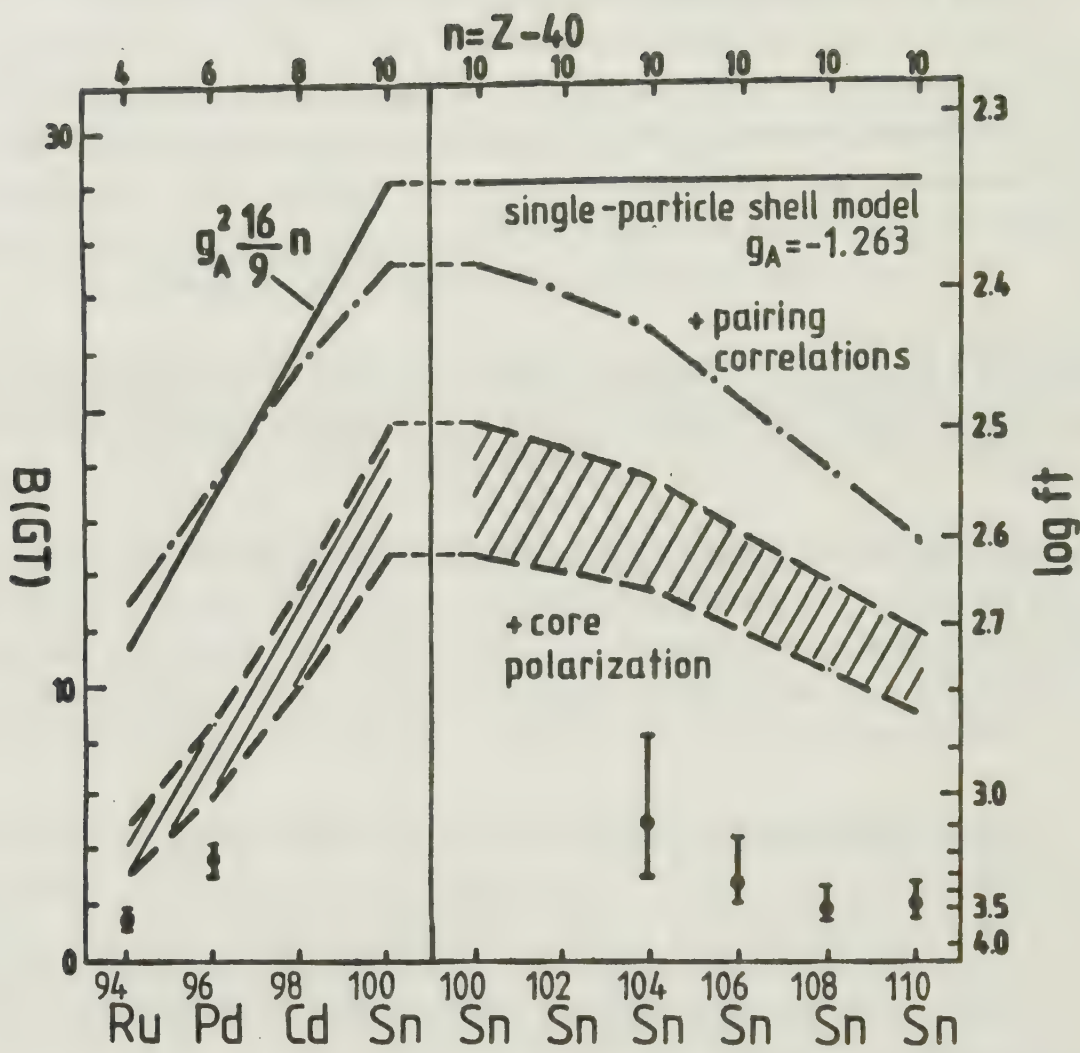


Figure 27. Compilation of the effect of the different hindrance factors from refs. [14,38] on the log ft values for N = 50 and Z = 50 nuclei (see text; the figure is taken from ref. [52]).

9.0 Predicted Properties of ^{100}Sn and ^{100}In

The nucleus ^{100}Sn is predicted to be bound against proton decay by $\cong 3$ MeV (ref. [52]), and to be spherical (ref. [42]). From the excellent agreement of the Model II-def. calculations with the experimentally determined Q_{EC} values for $^{108,106,104}\text{Sn}$ we conclude that we can reliably extrapolate to the $^{100}\text{Sn} \rightarrow ^{100}\text{In}$ decay, to yield $Q_{\text{EC}} = 7.82$ MeV.

The energy of the excited $|\pi g_{9/2}^9 \nu g_{7/2}, 1^+ \rangle$ state in ^{100}In is much more difficult to estimate. The Model II-def. calculations yield $E_{1^+} = 1.78$ MeV. Alternatively the Pandya transformation was used to predict the level structure of the particle-hole nucleus ^{100}In from the known levels of the particle-particle nucleus ^{92}Nb , and the 1^+ state is predicted to lie at 3.08 MeV (see ref. [44]). Since ^{100}In is predicted to be proton-unstable at $\cong 3$ MeV excitation energy (see ref. [52]), the actual energy of the 1^+ state would not only be of influence on the half-life of ^{100}Sn , but also be crucial for the observation of beta-delayed proton decay.

In order to estimate the transition probability for the Gamow-Teller decay we have used $E_{1^+} = 1.78$ MeV. The hindrance factor for pairing, $h_{\text{pair}} = 1.12$ (ref. [42]) and for core polarization, $h_{\text{cp}} = 1.29 - 1.71$ (ref. [14]), was used to deduce a predicted $\log ft$ value between 2.50 and 2.62. From these we obtain $T_{1/2}^{\text{sp}}(^{100}\text{Sn}) = 0.11$ s for the single particle estimates, and $T_{1/2}^{\text{quenched}}(^{100}\text{Sn}) = (0.14 - 0.19)$ s. Additional higher order effects, with $h_{\text{ho}} \cong 1.6$ as suggested by Towner (ref. [14]), or around 4, as deduced experimentally from this work, would change the half-life values to $(0.22 - 0.30)$ s or $(0.56 - 0.76)$ s, respectively. If the excitation energy of the 1^+ state were 3.08 MeV, these estimates would be changed to $(0.86 - 1.14)$ s for a hindrance factor of 1.6 and $(2.15 - 2.85)$ s using a hindrance being a factor of 4. Our predicted decay scheme for ^{100}Sn is shown in Fig. 28.

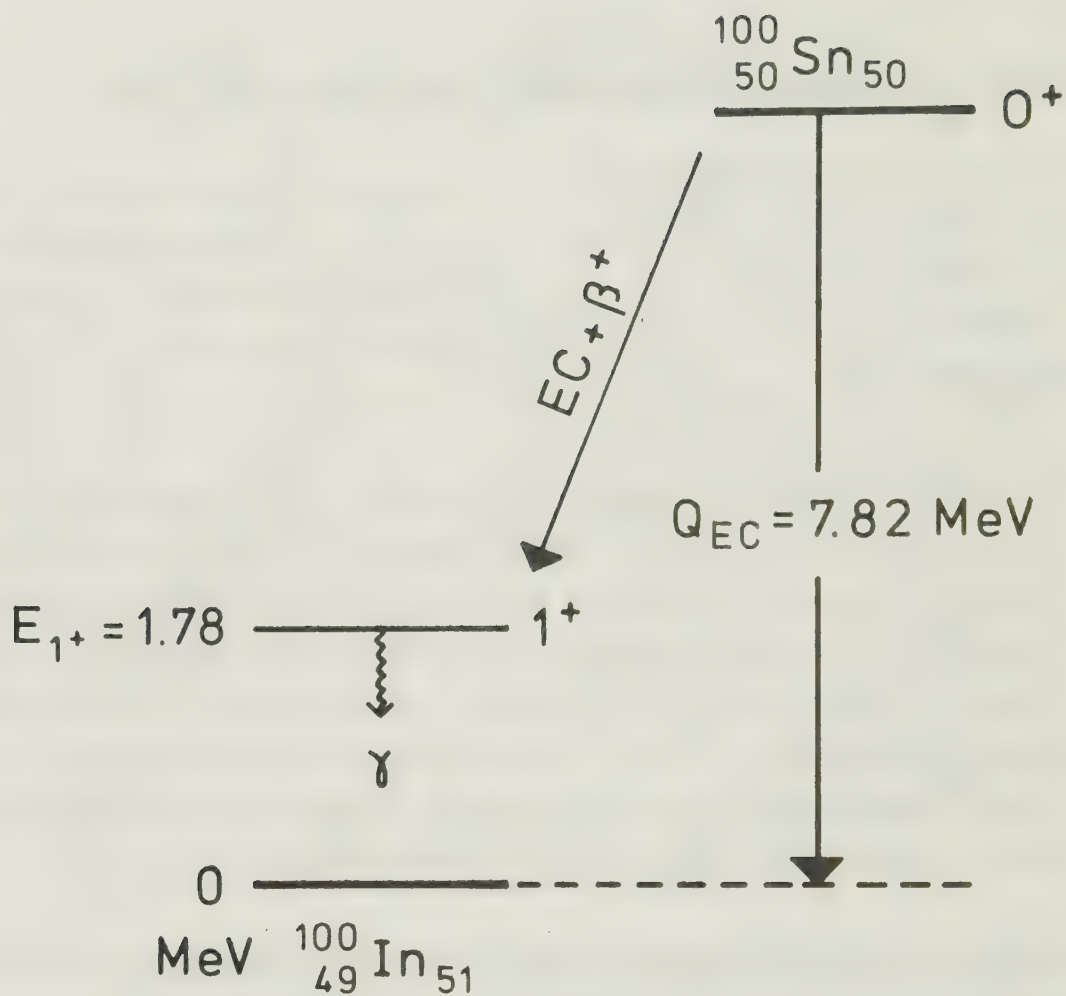


Figure 28. Predicted decay scheme of ^{100}Sn

10.0 Summary and Conclusions

In this work we have produced the neutron-deficient $^{108,106,104}\text{Sn}$ isotopes by heavy ion fusion reactions, and studied their decay properties using the GSI mass separator on-line to the UNILAC. Earlier information on the $^{108}\text{Sn} \rightarrow ^{108}\text{In}$ and $^{106}\text{Sn} \rightarrow ^{106}\text{In}$ decay schemes was complemented and improved in the course of this investigation.

The new nucleus ^{104}Sn and its decay to excited states in ^{104}In was identified and studied for the first time. Since this nucleus can only be produced with very low cross section, and a high isobaric background, two new experimental tools had to be developed:

1. The bunched release mode of the FEBIAD ion source (see ref. [26]), which allows a 'chemical selection' for the first time in an on-line mass separator facility;
2. A newly constructed mini-orange beta spectrometer of high resolution and large solid angle (see ref. [34]) which allowed to disentangle the complicated ^{104}In level scheme and to assign multipolarities to low energy electromagnetic transitions.

It was thus possible to determine the Q_{EC} value of ^{104}Sn and to localize 1^+ states in ^{104}In populated in the beta decay. Together with the half-life value of ^{104}Sn , $T_{1/2} = (21 \pm 1) \text{ s}$, we thus obtain the summed GT beta transition strength.

Our studies of the $^{104,106,108}\text{Sn}$ decays yield the following additional results:

1. Estimates for masses of nuclei close to the proton drip line, like ^{104}Sn , and of those linked to ^{104}Sn by alpha decay and proton radioactivity, like ^{108}Te , ^{109}I , ^{112}Xe , and ^{113}Cs .
2. Information on the quenching of the GT beta decay strength of the even neutron-deficient tin isotopes.

3. Localization of the $|\pi g_{9/2}^{-1} \nu g_{7/2}, 1^+\rangle$ magnetic dipole type excitation in odd-odd indium nuclei and on its fractionation due to residual interactions.

The information on the masses, together with similar relevant information in this region of the chart of nuclides helps to map out the mass-surface in some detail. Previous information on this question is summarized by Hamilton, Hansen and Zganjar (ref. [59]).

The quenching of the GT strength as observed for the $^{104,106,108,110}\text{Sn}$ nuclei complements similar information on the $N = 50$ nuclei ^{94}Ru and ^{96}Pd (see ref. [54]). Neutron pairing is still of dominant importance, even for ^{104}Sn with only four neutrons outside the magic $N = 50$ configuration. The $Z = 50$ proton shell appears to be remarkably stable, independent of the neutron number, in a wide range, $54 \leq N \leq 132$.

The $(\vec{\sigma}_1 \vec{\sigma}_2)(\vec{\tau}_1 \vec{\tau}_2)$ residual interaction becomes very important near ^{100}Sn , because the relevant shell model orbitals are rather closely spaced - although across the gap -, and neutrons and protons occupy orbitals with the same angular momentum l , thus having large spatial overlap. Therefore the Arima and Horie (ref. [57]) type of core polarization becomes of dominant influence, and is one main reason for the quenching of the GT strength in this region of the nuclear chart.

The experimental data on the GT strength are still lower, by factors of 2 - 4, than the 'best' theoretical estimates, which include pairing between like nucleons and core polarization of the spin-orbit partner type. This suggests that 'higher order phenomena' of various origins have to be taken into account. In addition it might well be possible that pairing between unlike nucleons, presumably of the singlet and triplet type, becomes of importance for the properties of the ^{100}Sn nucleus. To our knowledge this question has not yet been addressed by theoretical work.

The spreading of the $|\pi g_{9/2}^{-1} \nu g_{7/2}, 1^+\rangle$ configuration over several states in neutron deficient indium isotopes and in ^{94}Tc and ^{96}Rh appears to be a rather unique feature for the ^{100}Sn region. The calculations of Dobaczewski et al. (ref. [42]) show that the splitting due to deformation effects is too small. Therefore the coupling to the 2^+ core excitations appears to be important, in particular via the $[(\nu d_{5/2} \nu g_{7/2})_2^+ \times (\pi g_{9/2}^9 \nu g_{7/2})_1^+]_1^+$ component. This question has to our knowledge not been discussed theoretically for these nuclei.

As an outlook we speculate about future developments:

1. What are the chances to produce and identify nuclei near ^{100}Sn , and to study their decay?

It appears that $^{98}_{48}\text{Cd}_{50}$ can be produced and studied at the ISOLDE facility in the near future. The ^{102}Sn nucleus has been reached already from the alpha decay of ^{106}Te (ref. [44]), but with extremely low yield, therefore there is no information on its half-life and decay properties.

Fusion reactions with existing, i.e. stable projectile-target combinations appear to be unsuited to produce ^{100}Sn directly. Radioactive targets and radioactive beams, as provided by the new SIS-ESR facility of the GSI, may be a possible way to reach this goal. Another one might be projectile and/or target fragmentation, which yet has to be explored.

2. What do we expect for the ultimate single particle limit of GT decays?

Nuclei near ^{100}Sn are expected to yield information on the 'subnuclear' degrees of freedom in nuclei, in particular the role of the Δ -nucleon-hole excitation on the quenching of observables connected to the magnetic dipole operator. One needs, however, to reliably estimate the influence of pairing and of the importance of the 1^+ dipole state. Two suggestions are appropriate, in order to approach these problems:

- a. Studies on static magnetic dipole moments, and on M1, M3 transition probabilities may help to elucidate on the role of the core polarization. Collinear laser techniques and nuclear orientation on-line for nuclei near ^{100}Sn would be of use, with respect to the dipole moments. In this context we want to mention that we have obtained one such information, namely on the M3 deexcitation of the 16 s isomer in ^{104}In , which urgently needs a theoretical interpretation.
- b. The role of pairing between like nucleons has been considered already by recent theoretical calculations (ref. [42]). In order to test these calculations we suggest to obtain additional information on the beta and gamma decays in odd A nuclei, and to study in-beam gamma ray spectra to derive moments of inertia for rotational-like structures.

Since shape coexistence is a known phenomenon for tin nuclei (see ref. [59]) in the middle of the $50 \leq N \leq 82$ shell, and the ^{90}Zr or ^{88}Sr core is not a very stabilizing one we expect a rather delicate balance between the mean field, which defines the magicity of the $N = Z = 50$ core, and the residual interactions: pairing, which keeps the nuclear shape spherical, but influences transition probabilities, and the quadrupole type residual interaction, which determines deformation effects.

3. A third, speculative suggestion, again uses the future SIS-ESR facility, with its option to obtain radioactive 'exotic' beams. Should it be possible to produce very neutron-deficient tin, antimony, and tellurium radioactive beams, one would study the (p,t) and $(p,^3\text{He})$ reactions by the techniques discussed by W. Wagner (ref. [60]) on these nuclei, and thus learn about the role of pairing correlations between like and unlike nucleons for the properties of nuclei near ^{100}Sn .

Thus this work concludes by suggestions for new experiments, in particular at the new SIS-ESR facility of the GSI. It is our hope that the present investigation has helped to improve our knowledge on the properties of nuclei near ^{100}Sn , and on the quenching of the GT beta strength in situations where nuclear wave functions are rather well defined.

11.0 References

1. Détraz, C.: Proc. Int. Conf. of Nucl. Physics (IUPAP), Harrogate 1986, to be published
2. Lister, J.C.: *ibid*
3. Twin, P.J.: *ibid*
4. Münzenberg, G.: Proc. Symp. 10 Years of Uranium Beams, GSI Darmstadt 1986, to be published
5. Klepper, O.: *ibid*
6. Grant, I.S., Kirchner, R., Klepper, O., Koslowsky, V.T., Larsson, P.O., Nolte, E., Nyman, G., Plochocki, A., Rathke, G.-E., Roeckl, E., Rykaczewski, K., Schardt, D., Spanier, L., Tidemand-Petersson, P., Zganjar, E.F., Zylicz, J.: Proc. 7th Int. Conf. on Atomic Masses and Fundamental Constants AMCO-7, Klepper, O. (ed.), Darmstadt-Seeheim (1984) p. 170
7. Jänecke, J. and Eynon, B.P.: At. Data and Nucl. Data Tables **17**, 467 (1976)
8. Plochocki, A., Gowdy, G.M., Kirchner, R., Klepper, O., Reisdorf, W., Roeckl, E., Tidemand-Petersson, P., Zylicz, J., Schrewe, U., Kantus, R., von Dincklage, R.-D., Schmidt-Ott, W.D.: Nucl. Phys. **A332**, 29 (1979)
9. Bruske, C., Burkard, K.H., Hüller, W., Kirchner, R., Klepper, O., Roeckl, E.: Nucl. Instr. and Meth. **186**, 61 (1981)
10. Rathke, G.-E., Rykaczewski, K., Kirchner, R., Klepper, O., Koslowsky, V.T., Roeckl, E., Schardt, D., Grant, I.S., Larsson, P.O., Plochocki, A., Zylicz, J., Tidemand-Petersson, P.: Z.Phys. **A321**, 599 (1985)

11. Goodman, C.D.: Proc. Int. Conf. on Nucl. Phys., Blasi, P. and Ricci, R.A. (eds.),
Tipografia Compositori Bologna, p. 165 (1983)
12. Vogt, E.: Proc. Int. Conf. of Nucl. Physics (IUPAP), Harrogate 1986, to be published
13. Richter, A.: Proc. Int. Conf. on Nucl. Phys., Blasi, P. and Ricci, R.A. (eds.),
Tipografia Compositori Bologna, p. 189 (1983)
14. Towner, I.S.: Nucl. Phys. **A444**, 402 (1985)
15. Zylicz, J.: CERN-Proposal IP-20 (1985)
16. Björnstad, T., Borge, M.J.G., Blomqvist, J., von Dincklage, R.D., Ewan, G.T.,
off, P., Jonson, B., Kawade, K., Kerek, A., Klepper, O., Lövhöiden, G.,
Mattsson, S., Nyman, G., Ravn, H.L., Rudstam, G., Sistemich, K., Tengblad, O.:
CERN-EP/85-201 (1985)
17. Wilczynski, J.: Proc. Int. Conf. on Nucl. Phys., Blasi, P. and Ricci, R.A. (eds.),
Tipografia Compositori Bologna, p. 189 (1983)
18. "ISOLDE User's Guide" Kluge, H.J. (ed.): CERN 86-05 (1986)
19. Symons, J.M., Vivyogi, Y.P., Westfall, G.D., Doll, P., Greiner, D.E., Faraggi, H.,
Lindstrom, P.J., Scott, D.K., Crawford, H.J., MacParland, C.: Phys. Rev. Lett.
42, 40 (1979)
20. Kienle, P.: Proc. Symp. 10 Years of Uranium Beams, GSI Darmstadt 1986, to be published
21. Körner, H.J.: *ibid*
22. Gralla, S., Albinski, J., Bock, R., Gobbi, A., Herrmann, N., Hildenbrand, K.D.,
Kuzminski, J., Müller, W.F.J., Petrovici, M., Stelzer, H., Töke, J.,
Wollersheim, H.J., Olmi, A., Maurenzig, P.R., Stefanini, A.A.: Phys. Rev. Lett.
54, 1898 (1985)
23. Rykaczewski, K., Kirchner, R., Klepper, O., Koslowsky, V.T., Larsson, P.O.,
Rathke, G.-E., Roeckl, E., Schardt, D., Zganjar, E.F., Bosch, U., Eschner, W.,
Gippert, K.-L., Runte, E., Schmidt-Ott, W.-D., Tidemand-Petersson, P.,
Kaffrell, N., Peuser, P., Kurcewicz, W., Bernas, M., Dessagne, P., Langevin, M.,

- Beer, H., Walter, G.: Proc. XXIII Int. Wintemeeting on Nucl. Phys., Bormio 1985, p. 764
24. Eschner, W., Schmidt-Ott, W.-D., Gippert, K.-L., Runte, E., Beer, H., Walter, G.: Kirchner, R., Klepper, O., Roeckl, E., Schardt, D.: Z.Phys. **A317**, 289 (1984)
 25. Langevin, M., Quiniou, E., Bernas, M., Galin, J., Jacmart, J.C., Naulin, F., Pougheon, F., Anne, R., Détraz, C., Guerreau, D., Guillemaud-Müller, D., Müller, A.C.: Phys. Lett. **150B**, 71 (1985)
 26. Kirchner, R., Klepper, O., Marx, D., Rathke, G.-E., Sherrill, B.: Nucl. Instr. and Meth. **A247**, 265 (1986)
 27. Kirchner, R. and Roeckl, E.: Nucl. Instr. Meth. **133**, 187 (1976)
 28. Roeckl, E. and Klepper, O.: GSI-Nachrichten 09-86 (1986)
 29. GSI-Experiment 201, unpublished
 30. Huyse, M., private communication 1984
 31. Reisdorf, W.: Z.Phys. **A300**, 227 (1981) and GSI-Rep. 81-2, 73 (1981)
 32. Thomas, T.D.: Ann. Rev. Nucl. Sci. **18**, 343 (1968)
 33. Bolsterli, M., Fiset, E.O., Nix, J.R., Norton, J.L.: Phys. Rev. **C5**, 1050 (1972)
 34. Barden, R.: Thesis, GSI Darmstadt, to be published
 35. Busch, F., Croome, D., Göringer, H., Hartmann, V., Lowsky, J., Marinescu, D., Richter, M., Winkelmann, K.: GSI-83-4, ISSN 0171-4546 (1983)
 36. Lederer, C.M. and Shirley, V.S. (eds.): Table of Isotopes 7th ed. (1978)
 37. Plochocki, A., Zylicz, J., Kirchner, R., Klepper, O., Roeckl, E., Tidemand-Petersson, P., Grant, I.S., Misaelides, P.: Nucl.Phys. **A388**, 91 (1982)
 38. Harmatz, B.: Nucl. Data Sheets **30**, 305 (1980)
 39. Dzelepov, B.S., Zyryanova, L.N., Suslov, Y.P.: Beta Processes, Nauka, Leningrad 1972

40. Rösel, F., Fries, H.M., Alder, K., Pauli, H.C.: *At. Data and Nucl. Data Tables* **21**, 110 (1978)
41. Eberz, J., Dinger, U., Huber, G., Lochmann, H., Menges, R., Neugart, R., Kirchner, R., Klepper, O., Kühl, T., Marx, D., Ulm, G., Wendt, K.: GSI-Preprint 86-22 and to be published in *Nucl. Phys. A*
42. Dobaczewski, J., Nazarewicz, W., Plochocki, A., Rykaczewski, K., Zylicz, J.: *Proc. Int. Conf. W.E.I.N., Heidelberg (1986)*, to be published
43. Möller, P. and Nix, J.R.: *Nucl. Phys.* **A361**, 117 (1981)
44. Stone, C.A. and Walters, W.B.: *Hyp. Int.* **22**, 363 (1985)
45. Dewberry, R.A., Kouzes, R.T., Naumann, R.A.: *Phys. Rev.* **C27**, 27 (1983)
46. Huang, H., Pathak, B.P., Lee, J.K.P.: *Can. J. Phys.* **56**, 936 (1978)
47. Wouters, J.M., Thierens, H.M., Äystö, J., Cable, M.D., Haustein, P.E., Parry, R.F., Cerny, J.: *Phys. Rev.* **C27**, 1745 (1983)
48. Schardt, D., Batsch, T., Kirchner, R., Klepper, O., Kurcewicz, W., Roeckl, E., Tidemand-Petersson, P.: *Nucl. Phys.* **A368**, 153 (1981)
49. Hoffmann, S., Agarwal, Y.K., Armbruster, P., Heßberger, F.P., Larsson, P.O., Münzenberg, G., Poppensieker, K., Reisdorf, W., Schneider, J.R.H., Schött, H.J.: *Proc. 7th Int. Conf. on Atomic Masses and Fundamental Constants AMCO-7*, Klepper, O. (ed.), Darmstadt-Seeheim (1984) p. 184
50. Schmidt, K.-H., Faust, W., Münzenberg, G., Clerc, H.-G., Lang, W., Pielenz, K., Vermeulen, D., Wohlfahrt, H., Ewald, H., Güttner, U.: *Nucl. Phys.* **A318**, 253 (1979)
51. Wapstra, A.H. and Audi, G.: 1983 Mass Tables, *Nucl. Phys.* **A432**, 1 (1985)
52. Leander, G.A., Dudek, J., Nazarewicz, W., Nix, J.R., Quentin, P.H.: *Phys. Rev.* **C30**, 416 (1984)
53. Rykaczewski, K., Grant, I.S., Kirchner, R., Klepper, O., Koslowsky, V.T., Larsson, P.O., Nolte, E., Nyman, G., Roeckl, E., Schardt, D., Spanier, L., Tidemand-Petersson, P., Zganjar, E.F., Zylicz, J.: *Z. Phys.* **A322**, 263 (1985)

54. van Maldeghem, J., Heyde, K., Sau, J.: Phys. Rev. **C32**,1067(1985)
55. Bohr, A. and Mottelson, B.: Nuclear Structure, Benjamin New York (1969)
56. Klepper, O.: Proc. Int. Conf. W.E.I.N., Heidelberg (1986), to be published
57. Arima, A. and Horie, H.: Prog. Theo. Phys. **11**, 509 (1954)
58. Grotz, K., Klapdor, H.V., Metzinger, J.: Phys. Lett. **132B**, 22 (1983)
59. Hamilton, J.H., Hansen, P.G., Zganjar, E.F.: Rep. Prog. Phys. **48**, 631 (1985)
60. Wagner, W.: Thesis Tech. Univ. München, 1986

12.0 Appendix

12.1 Danksagung

An dieser Stelle möchte ich allen jenen danken, die am Zustandekommen dieser Arbeit beteiligt waren.

An den Anfang möchte ich alle diejenigen stellen, die mitunter in ihren Serviceeinrichtungen anonym bleiben, wie die Mitarbeiter von UNILAC, Rechenzentrum, Experimentelektronik und Targetlabor, ohne deren Mithilfe ein Experimentieren nicht möglich gewesen wäre.

Mein besonderer Dank jedoch gilt

Prof. Ernst Roeckl, der es erst ermöglicht hat, daß ich dieses attraktive Thema bearbeiten konnte,

Prof. Jan Zylicz, der sich kontinuierlich um die Arbeit gekümmert und sie vorangetrieben hat,

Prof. Andrzej Plochocki und **Dr. Krzysztof Rykaczewski**, die immer schnell und effektiv zur Datenauswertung beigetragen haben,

Dr. Dieter Schardt, der mich in die Geheimnisse des Computers eingeweiht hat,

Dr. Reinhard Kirchner, durch dessen Ionenquellen-Artistik saubere Messungen gemacht werden konnten,

Raimund Barden, der in Windeseile das Elektron-Spektrometer zum Laufen brachte,

Dr. Otto Klepper, der immer alle notwendigen Zahlen parat hatte,

Christoph Bruske, **Karlheinz Burkard** und **Wilfried Hüller**, die sich - wie die oben erwähnten auch - in Strahlzeiten die Nächte um die Ohren schlugen,

Drs. Dobaczewski und **Nazarewicz**, die - veranlaßt durch unsere experimentellen Ergebnisse - bereit waren, Rechnungen durchzuführen

Dr. Dieter Marx, **Dr. Thomas Kühl** und **Dr. Jürgen Eberz**, die immer zu Diskussionen bereit waren,

Annemarie Knispel, die blitzschnell viele Bilder fabriziert hat,

Irmgard Poppert, die die Arbeit in Form gebracht hat

und

Prof. Hans-Joachim Körner - ohne den ich jetzt nicht so weit wäre.

12.2 Curriculum Vitae

Gabriele - Elisabeth Rathke

Mauerkircherstr. 168

8000 München 81

Ich, Gabriele - Elisabeth Rathke, wurde am 12. Januar 1958 als einziges Kind des Bau - Ingenieurs Siegfried Rathke (gest. 21.2.77) und der Hausfrau Irmgard Rathke geb. Müller (gest. 4.7.80) in München geboren.

Die Grundschule absolvierte ich von 1964 - 1968 an der Gebeleschule in München. Anschließend besuchte ich das Gymnasium Max - Josef - Stift in München, wo ich am 23.6.1977 die Allgemeine Hochschulreife erlangte.

Im November 1977 begann ich das Studium der allgemeinen Physik an der Technischen Universität München, wo ich am 20.10.80 das Vordiplom erwarb. Im Juli 1982 absolvierte ich meine Prüfungen zum Diplom und begann im Oktober 1982 mit einer experimentellen Diplomarbeit mit dem Thema "Gamma - spektroskopische Untersuchung von protonenreichen Kernen der Seltenen Erden in der Gegend um $N = 84$ " bei Professor H. Morinaga. Diese Arbeit war im Januar 1984 beendet und am 23.1.1984 erhielt ich mein Diplom.

Seit Mai 1984 arbeite ich bei der GSI (Gesellschaft für Schwerionenforschung) in Darmstadt bei Professor E. Roeckl an der vorliegenden Arbeit.

